RESOURCE CAPTURE AND PRODUCTIVITY OF AGROFORESTRY SYSTEMS IN KENYA

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ABSTRACT

Resource capture and utilisation were studied in two agroforestry systems at the International Centre for Research in Agroforestry (ICRAF) Research Station at Machakos, Kenya. The agroforestry systems examined contained two contrasting tree species, leucaena (Leucaena leucocephala (Lam.) de wit) and grevillea (Grevillea robusta), and the C3 and C4 crops, cowpea (Vigna unguiculata) and maize (Zea mays, Katumani composite).

The leucaena-based trial was established in November 1989 and the trees were grown with ten maize crop rows on either side of a pruned hedgerow (HM) or unpruned tree row (LM). A sole maize control (SM) was also grown. Paired sets of treatments were irrigated to eliminate below-ground competition for water (HMI, LMI and SMI respectively). Interception of photosynthetically active radiation (PAR) by leucaena and maize was measured on a row-wise basis in all treatments at 7-10 day intervals using a sunfleck ceptometer. Sap flux was measured for the maize and both pruned and unpruned leucaena using heat balance gauges. Results are presented for the 1992 April-July rainy season.

Total PAR interception was 30 % greater in LM and LMI than in the SM and SMI sole maize treatments. However, little more than 30 % of the light intercepted by the LM and LMI systems was captured by the crop component, and competition for light alone reduced maize yields by over 30 %. Total water uptake by the LM leucaena and maize comprised 60 % of the seasonal rainfall (237 mm) as compared to 30 % for sole maize. However, as for light interception, only 30 % of the water transpired in LM was used by the intercropped maize, and competition from the trees for soil water reduced maize yields at distances of over 6 m from the leucaena. The leucaena was more effective at resource capture, yet less efficient in resource utilisation since it exhibited a lower dry matter:radiation quotient and a lower transpired water:dry matter ratio than maize. Thus the leucaena in the agroforestry systems captured more of the resources that could have been used more effectively by the maize, causing the performance of the mixture to be sub-optimal; these results suggest that the two components would be best grown separately.

Intensive monitoring of resource capture and use by trees and crops was subsequently transferred to the Complementarity In Resource Use on Sloping land trial (CIRUS). Although it had been intended to study both trials during the long rains of 1993, the leucaena trees were almost completely defoliated by psyllid (Heteropsylla cubana) infestation shortly before the onset of the rains: in subsequent seasons, CIRUS was studied in preference to the leucaena trial as the trees had only partially recovered.

CIRUS was designed to investigate the effects of competition and the extent of

complementarity between grevillea and associated crops using the following treatments; sole crops (Cg) of cowpea during the short rains and maize during the long rains, dispersed-planted trees with (CTd) and without crops (Td), and across (CTa) or on-contour-planted (CTc) tree rows with crops. Light interception and water use were monitored using a similar measurement regime to that employed in the leucaena trial. Results are presented for the 1992/3 and 1993/4 short rainy seasons; the failure of the 1993 long rains forced the abandonment of experimental measurements during this season.

Light interception by the Td and CTd grevillea increased greatly between the two short rainy seasons. Thus, total seasonal interception of PAR was three times greater in sole cowpea than in sole grevillea during the 1992/3 short rains, but by the following short rainy season was over 50 % greater in the grevillea than in the cowpea. Cumulative interception of PAR by the CTd grevillea and cowpea combined was more than twice that of the sole cowpea and over 40 % greater than that for sole grevillea during the 1993/4 short rains. Experiments involving artificially imposed shade showed that there was no reduction in total above-ground dry matter production in cowpea until 75 % shading was imposed.

To quantify the degree of below-ground complementarity in water use between grevillea and cowpea, sap flux was measured using heat balance gauges attached to the stems of young grevillea (10-18 months old), both before and after excavating the crop rooting zone (upper 60 cm of soil) around the stem base. The crop rooting zone was removed to establish the capability of the grevillea to extract water from deeper horizons. After excavation, the trees maintained sap fluxes of up to 85 % of the unexcavated values. During both short rains, soil evaporation was by far the largest component of the water balance in all treatments. However, continued extraction of water by the trees during the dry season greatly increased resource capture; thus total water uptake was three times greater for the sole trees than for the sole crop when dry season water use was included. During the 1993/4 short rains, water use was greatest in the CTd treatment, in which 25 % of the total seasonal rainfall was transpired by the trees and crops. Although transpiration by the CTd trees exceeded interception losses, the latter may have had a greater effect on crop growth by reducing the total quantity of water available within the system. The existence of below-ground complementarity and the shade tolerance of the cowpea suggest that deep-rooted tree species and certain C3 crops may be combined successfully in the semi-arid tropics, but the sensitivity of crop yield to any reduction in water availability within the system demonstrates the need for caution when implementing such systems.

The results obtained are discussed in relation to previous research on intercropping and agroforestry and their implications for the successful adoption of agroforestry systems in the semi-arid tropics.

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LIST OF SYMBOLS AND ABBREVIATIONS[1]

General

CPR	Crop performance ratio
DAE	Days after emergence
DAP	Days after planting
DAS	Days after sowing
LER	Land equivalent ratio
PAR	Photosynthetically active radiation
RYT	Relative yield totals
T or t	Time

Allometrics

A	Area
BD	Basal diameter
DBH	Diameter at breast height
H	Height
L	Leaf area
LAI	Leaf area index
L_n	Leaf number
SLA	Specific leaf area
W	Mass
V	Volume

Light

I	Incident radiation above the canopy
k	Extinction coefficient
f	Fractional interception
f_s	Fractional interception of total shortwave solar radiation
f_p	Fractional interception of PAR
Cf_p	Fractional interception of PAR by the cowpea
Tf_p	Fractional interception of PAR by the trees
Mf_p	Fractional interception of PAR by the maize
Sf_p	Fractional interception of PAR by the system
f_t	Fraction of radiation transmitted through the canopy
S_p	Total cumulative PAR interception
e	Dry matter:radiation quotient
e_p	Dry matter:radiation quotient (PAR)

Water balance

P	Rainfall

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[1] This list of symbols and abbreviations is not exhaustive and contains only those used most commonly. All other symbols and abbreviations are defined at the point of use.

E or E_t	Transpiration
I	Interception losses
E_s or e_s	Soil evaporation
U	First stage soil evaporation evaporation
α	The second stage soil evaporation constant
R	Runoff
D_r	Drainage (deep percolation and lateral flow)
S	Change in water storage within the soil profile
VSM	Volumetric soil moisture content
WSM	Gravimetric soil moisture content
ET_0	Potential evapotranspiration
R_n	Net radiation
G	Soil heat flux
ρ_a	Density of air
D	Saturation vapour pressure deficit
D	Saturation vapour pressure deficit adjusted per unit of transpiration
e_w	Dry matter:transpired water ratio
r_c	Canopy resistance
r_s	Stomatal resistance
r_a	Boundary layer resistance

ABG trial

ABG	Above and below-ground competition trial
SM	Rainfed sole maize treatment in ABG
LM	Rainfed upperstorey leucaena with maize treatment in ABG
HM	Rainfed hedgerow leucaena with maize treatment in ABG
SMI	Irrigated sole maize treatment in ABG
LMI	Irrigated upperstorey leucaena with maize treatment in ABG
HMI	Irrigated hedgerow leucaena with maize treatment in ABG

CIRUS trial

CIRUS	Complementarity in resource use on sloping land trial
Cg	Sole crop in CIRUS
CTd	Dispersed-planted trees with crops in CIRUS
CTc	Contour-planted (North-South) tree rows with crops in CIRUS
CTa	Across contour planted (East-West) tree rows with crops in CIRUS
Td	Dispersed-planted sole trees in CIRUS

Subscripts

l	Leaf
t	Trees
c	Crops
p	Photosynthetically active radiation
i	Incident radiation

ABOVE AND BELOW-GROUND COMPETITION IN LEUCAENA/ MAIZE AGROFORESTRY SYSTEMS

Plate 1 The overstorey leucaena canopy in the rainfed agroforestry treatment of the above and below-ground competition trial during the 1992/3 short rains.

CHAPTER 1

INTRODUCTION

1 GENERAL INTRODUCTION

Traditional farming systems have long relied on empirically determined knowledge of which crop combinations were most appropriate for specific soil or climatic conditions and which agroforestry systems provided the desired returns etc.: many of these systems took hundred or thousands of years to evolve. There are approximately 50,000 tropical tree species (R May, pers. com.), hundreds of crops with thousands of varieties and an enormously complex array of soils, topographies and climates. Given the complexity of the possible tree/crop combinations detailed, the need for a fundamental understanding of the processes of competition, complementarity, resource capture and use is obvious if new, effective and sustainable agroforestry systems are to be developed.

Section 1.2 outlines some of the existing agroforestry technologies and practices and, while not exhaustive, indicates the sheer number and complexity of these technologies, illustrating the difficulties faced in increasing our understanding in agroforestry in a way that is useful to farmers. Section 1.3 discusses competition and complementarity in intercrops and agroforestry, while sections 1.4 and 1.5 examine the principles of resource capture and use of light and water respectively. The crops and trees used in the trials are described in sections 1.6 and 1.7.

1.1 AGRICULTURE IN SUB-SAHARAN AFRICA

Sub-Saharan Africa is the only region in the developing world where per capita food production is declining (World Resources Institute, 1990). Climatically, an estimated 30 % of the continent could support rainfed agriculture of which approximately one quarter is currently in use; however, large areas are unsuitable for agriculture (c. 40% due to tsetse fly and c. 10 % due to the extremely high sand content in the soil;

World Resources Institute, 1990). Most tropical soils are far older than those in northern temperate regions and arable soils tend to be coarse with a low clay content, low moisture holding capacity and a tendency to be easily eroded, while >80% have some fertility limitation (Harrison, 1987). Low rainfall areas predominate, with interannual variability frequently reaching 40 %, and multiyear droughts are common across the region, extending from Ethiopia to South Africa (World Resources Institute, 1990).

Between 1964 and 1984 the cultivatable land area per person in Africa fell from 0.74 to 0.35 ha person^{-1} and several Sub-Saharan African countries changed from net exporters of food to net importers (Johnston, 1991). Prior to western colonisation, food security in the region relied on grain storage, with families or villages possessing substantial grain reserves to allow for the inevitable periods of drought (Page *et al.*, 1991). Traditional agricultural practices comprised various forms of shifting agriculture, in which fields were cropped for two or three years before being left fallow for at least ten years, with bushes, shrubs and trees promoting the restoration of soil fertility (Gelfand, 1971; World Resources Institute, 1990). Recent studies in western Kenya, where the average farm size is 1.2 ha, showed that only 10-25 % of the farm was in fallow for just one year at any one time (ICRAF, 1993). In Kenya and elsewhere, there is an accelerating process of intensification of land use and many former pastoralists, such as the Samburu and Masii, are turning to settled agriculture. Traditional farming involving diverse mixed cropping has largely been replaced by monocultures and in many areas diets are dependent to a large degree on maize, to the extent that food security is now discussed in terms of maize grain equivalent (World Bank, 1989; Page *et al.*, 1991). In the semi-arid zone, drought resistant crops such as millet (*Pennisetum typhoides*) and sorghum (*Sorghum bicolor*) have increasingly been replaced by maize, thereby increasing the risk of crop failure (Page *et al.*, 1991). Figure 1.1 shows the projected food gap for Sub-Saharan Africa, and indicates that the rate of population growth will have to be reduced to 2.75 % per annum and the rate of growth of food production doubled to 4 % for 30 years if the food gap is to be minimised (World Bank, 1989).

Fuelwood supplies 80 % of the region's energy demands and is in increasingly short supply (Nair, 1989; World Resources Institute, 1990). Figure 1.2 illustrates the potential

effect of fuelwood shortages on farming systems in semi-arid tropical regions. In much of the tropics, soil erosion is a far greater problem than in the temperate zone since approximately 40 % of rainfall is received at rates exceeding 25 mm h^{-1}, compared with only 5 % in the temperate zone (World Resources Institute, 1990). In southern Nigeria, Davis and Payne (1988) reported that erosion problems are a combination of the highly erosive rains, with approximately 14 % of storms exceeding100 mm h^{-1}, and the rapid decline in soil aggregation under cultivation.

According to the World Bank (1989), an estimated 50 % of the 11 m ha of forest felled each year are to provide replacement cropland for land that has gone out of production due to erosion and fertility losses. This is obviously a finite process and the challenge for African farmers and agricultural researchers is to stabilise, and where possible enhance, productivity on land that is currently in production. Given the increasing fuelwood shortages that are endemic to these regions, the challenge is to improve the productivity of both crops and trees.

1.2 AGROFORESTRY

The history of agroforestry

A detailed history of the development of agroforestry was given by King (1989) and a brief summary is provided here. Shifting cultivation is one of the oldest forms of agriculture, having been practiced for millennia and live-fences for the control of live-stock have been used for several centuries. In the early 19th century the Taungya system was developed in Burma, from where it spread. This system used local labour to establish teak plantations and then cultivate between the trees (King,1989). Also during the 19th century shade trees were introduced to tea and coffee plantations (Rao, 1961). Agroforestry practices are now wide-spread, ranging from the grazing of olive groves in the Mediterranean to the home gardens of Mt. Kilimanjaro (Joffre *et al.*, 1989; Fernandes *et al.*, 1989). However, until the mid-1970s, King (1989) suggests that little thought was given by researchers to the needs of the farmers.

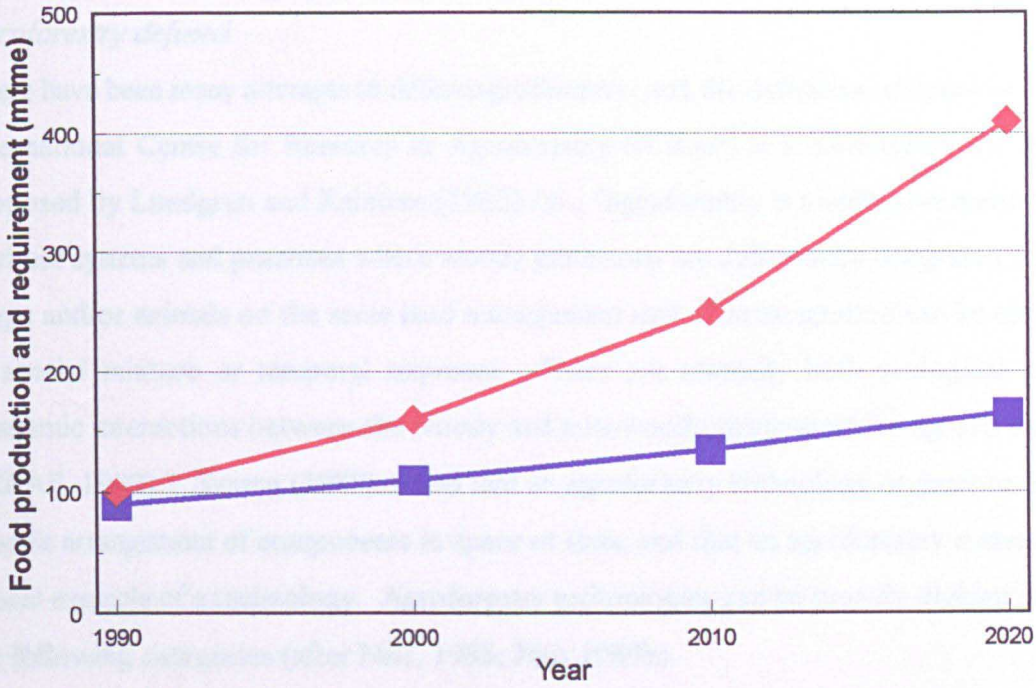

Figure 1.1 Projected food production (■) and requirement (◆) in millions of tons of maize equivalent (mtme) for Sub-Saharan Africa assuming population growth at constant fertility and food production increasing at 2% per year (Source: The World Bank, Sub-Saharan Africa: From Crises to Sustainable Growth, 1989).

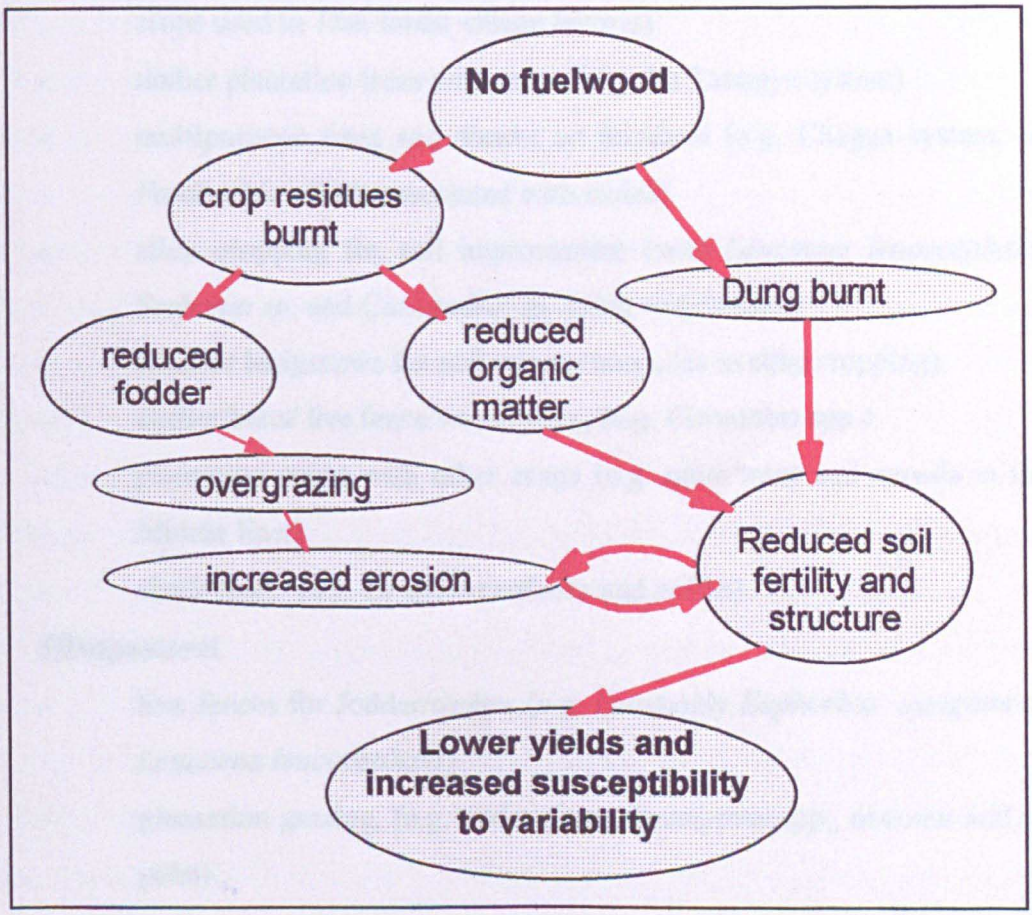

Figure 1.2 The potential impact of lack of fuelwood availability on agriculture.

Agroforestry defined

There have been many attempts to define agroforestry, and the definition adopted by the International Centre for Research in Agroforestry (ICRAF) is a modification of that proposed by Lundgren and Raintree (1982) i.e.., "agroforestry is a collective name for land-use systems and practices where woody perennials are deliberately integrated with crops and/or animals on the same land management unit. The integration can be either in spatial mixture or temporal sequence. There are normally both ecological and economic interactions between the woody and non-woody components in agroforestry (ICRAF, 1992)." Young (1988) stated that an agroforestry technology or practice is a specific arrangement of components in space or time, and that an agroforestry system is a local example of a technology. Agroforestry technologies can be broadly divided into the following categories (after Nair, 1985; Nair 1989b).

- **Agrisilvicultural**
  - improved fallows (e.g. *Sesbania sesban*, or fruit trees and plantation crops used in Thai forest village fallows)
  - timber plantation trees with crops (e.g. the Taungya system)
  - multipurpose trees and shrubs on farmland (e.g. Chagga system, or *Faidherbia albida* associated with maize)
  - alley cropping for soil improvement (with *Leucaena leucocephala*, *Sesbania sp.* and *Calliandra sp.* being widely used)
  - contour hedgerows for soil conservation, (as in alley cropping)
  - shelter belts/ live fence windbreaks, (e.g. *Casuarina* spp.)
  - plantation crops with other crops (e.g. olive trees and cereals in the Middle East)
  - shade trees (e.g. *Grevillea robusta* and coffee)
- **Silvopastoral**
  - live fences for fodder/shelter (e.g. commonly *Euphorbia syzigium* or *Leucaena leucocephala*)
  - plantation grazing, (e.g. under pines, *Eucalyptus* spp., coconut and oil palm)

- **Agrosilvopastoral**
  - alley cropping, for fodder (e.g. *Leucaena leucocephala* used in zero grazing)
  - homegardens (complex mixtures of woody and non-woody plants with an animal component)
- **Other systems**
  - aquaforestry (eg. fish fodder, integrated management of mangroves for fish, crustacea and timber),
  - apiculture with trees (common across east Africa),
  - traditional forms of shifting cultivation

The above list of technologies and practices is by no means exhaustive and the sheer number and complexity of these technologies illustrate the difficulties faced in increasing our understanding of agroforestry in ways that may benefit local farmers.

Benefits of agroforestry

Numerous discussions have considered the potential benefits of agroforestry systems (e.g. Kessler and Breman, 1991) some of which have subsequently been proved or disproved and some of which remain in doubt. Reductions in soil erosion and runoff by agroforestry are now well established (Young, 1986 & 1989; Lal, 1989; Kiepe, 1995). Improvements in soil physical properties such as infiltration rates and bulk density are also well documented, occurring within two or three seasons of establishment of the agroforestry systems (Van Noordwijk *et al.*, 1991; Dalland *et al.*, 1993; Kiepe, 1995). The transfer of nitrogen from leguminous species to associated crop now appears to be of little significance (Giller and Wilson, 1991). The extent to which trees can promote more effective nutrient cycling from deep soil horizons (Young, 1991), is still largely unknown. The suppression of weeds has been demonstrated in agroforestry systems (Jama, 1986), although the suppression of pests has only be shown in intercropping (Lawson and Jackai, 1987), however Stigter and Baldy (1995) have suggested that intercropping or agroforestry practices could diminish the visual attractiveness of the crop, thereby creating an unsuitable microhabitat for the pest, or posing physical barriers to their dispersal. Although this is a far from complete list, the principal benefits of

combining trees with crops lie in the increased capture or efficiency of use of resources, as is discussed at length later in this chapter.

1.3 COMPLEMENTARITY AND COMPETITION

Competition and complementarity defined

The term competition has been used in many different contexts and with many different definitions. Kershaw and Looney (1985) discussed competition as a process leading to negative or positive correlations or associations. However, competition is inherently the appropriate term for interactions resulting in a negative association. Pielou (1979) used the following definition, "competition takes place when the growth of a population, or any part of it, is slowed because at least one necessary factor is in short supply." However, since even an individual, such as an isolated tree, may suffer reduced growth due to limited supply of a necessary factor, a more appropriate definition is, "competition is the situation that arises when two or more organisms of the same or different species need the same limited resource (Tootill, 1984)." Thus, whenever plants are grown in a way where they interact spatially and temporally ,competition is likely to occur unless supplies of essential resources are unlimited.

Competition may be either interspecific when it occurs between different species, or intraspecific when it occurs between individuals of the same species. It has been suggested that competition is likely to be more severe between similar species then between species with differing niches or growth habits (Vandermeer, 1989). This is known as Gause's hypothesis, from which it follows that individuals of the same species will be similar and therefore intraspecific competition will tend to be greater than interspecific competition.

In natural ecosystems, the overall biomass is governed largely by competition, limitation of resources and disturbance such as fire or herbivory (Grime, 1974, 1977). In monocropped agricultural systems, disturbance can usually be controlled, but competition may only be modified by regulating population density and the inputs of resources (water and nutrients). An additional option for increasing overall growth is to reduce

competition by mixing species with different resource requirements. While competition is the appropriate term to describe interactions leading to a negative association, a positive association is better described in terms of complementarity. Ong (1995) defined complementarity as "the situation in which species experience less competition when grown in mixtures than in sole stands." Complementarity may result from either increases in resource capture or resource use efficiency (Stigter and Baldy, 1995) and may be either temporal or spatial. Gause's hypothesis was primarily developed for animal ecology and, unlike animals, all plants use the same resources, i.e. light, water, carbon dioxide and nutrients, so the potential for complementarity in resource capture is limited (Loomis and Connor, 1992; Ong et al., 1996). Spatial complementarity will occur in a mixture when the species occupy different niches, thereby allowing increased resource capture, such as when a shallow-rooted species is intercropped with a deep-rooting species. Temporal complementarity occurs when one species alone cannot fully exploit resources for the full duration of the growing season, such as a short duration legume or cereal, whereas a mixture of a fast-growing, short-duration crop and a slow-growing, long-duration crop would capture resources more fully over a longer period. Complementarity and competition for light and water are discussed further in Sections 1.4.and 1.5.

Overyielding, land equivalent ratio and relative yield total

If a mixture exploits resources more effectively (resulting from either by increases in resource capture or resource use efficiency) then overyielding will be exhibited and complementarity will occur (Fig. 1.3). However, if competition occurs in the absence of complementarity, then no overyielding will be exhibited regardless of the relative proportions of the species (Ong *et al.*, 1996). In order to establish whether a species mixture is overyielding, the relative yield totals (RYT) or land equivalent ratios (LER) can be calculated. Some authors prefer the use of the term crop performance ratio (CPR, eg. Azam-Ali *et al.*, 1990 and Azam-Ali 1995) because this implies differences in crop performance between the sole and intercrops. CPR is calculated as follows:

$$CPR_{ab} = \frac{(Y_{ai} + Y_{bi})}{[(P_{ai} \cdot Y_{as}) + (P_{bi} \cdot Y_{bs})]} \qquad \textbf{(Eq. 1.1)}$$

where Y_{ai} and Y_{as} represent the intercropped and sole crop yields for species a, P_{ai} is the proportion of the intercrop contributed by species a and Y_{bi}, Y_{bs} and P_{bi} are the corresponding values for species b. CPR is useful for analysing replacement series intercrops (where rows of one species are progressively substituted with rows of another species) in which the relative proportions of the intercrop can be easily calculated. However, when additive systems are used (where a second crop is added to another grown at its normal planting density, the same as the sole crop), RYT or LER are preferable.

RYT and LER values are numerically equivalent and LER is frequently preferred because it implies the optimisation of yield per unit area of land. LER represents the ratio of the land area required to produce the yields of the components of a mixture to the total land area covered by the mixture, and is calculated as follows (Loomis and Connor, 1992):

$$LER = \frac{Y_{ai}}{Y_{as}} + \frac{Y_{bi}}{Y_{bs}} \qquad \textbf{(Eq. 1.2)}$$

where LER is significantly >1 the mixture is regarded as overyielding and complementarity exists. It is essential that both the sole stands and mixtures are planted and managed optimally if the relative performance of the mixture is to be assessed reliably. Figure 1.4 shows the correct (a) and incorrect (b) basis for determining the efficiency of various systems and calculating the corresponding LER values. If the sole stands are sub-optimal (due, for instance, to a low density of tree planting), then the LER value for the mixture will be artificially high and a positive interaction maybe assumed where none exists. It has been suggested that most of the reported LER values involve errors of this kind (Loomis and Connor, 1992; Rao and Coe, 1992), emphasising the critical importance of sound experimental design and analysis.

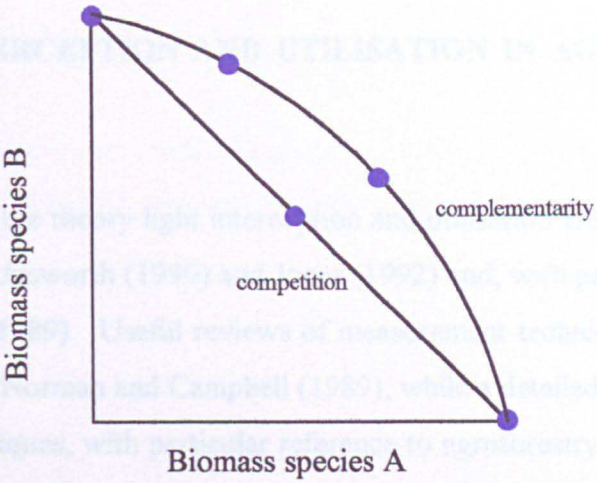

Figure 1.3 Competition and complementarity in a theoretical mixture. Where complementarity occurs the mixture will overyield and be outside the hypotenuse. When competition occurs there will be no overyielding (after Ong *et al.*, 1996).

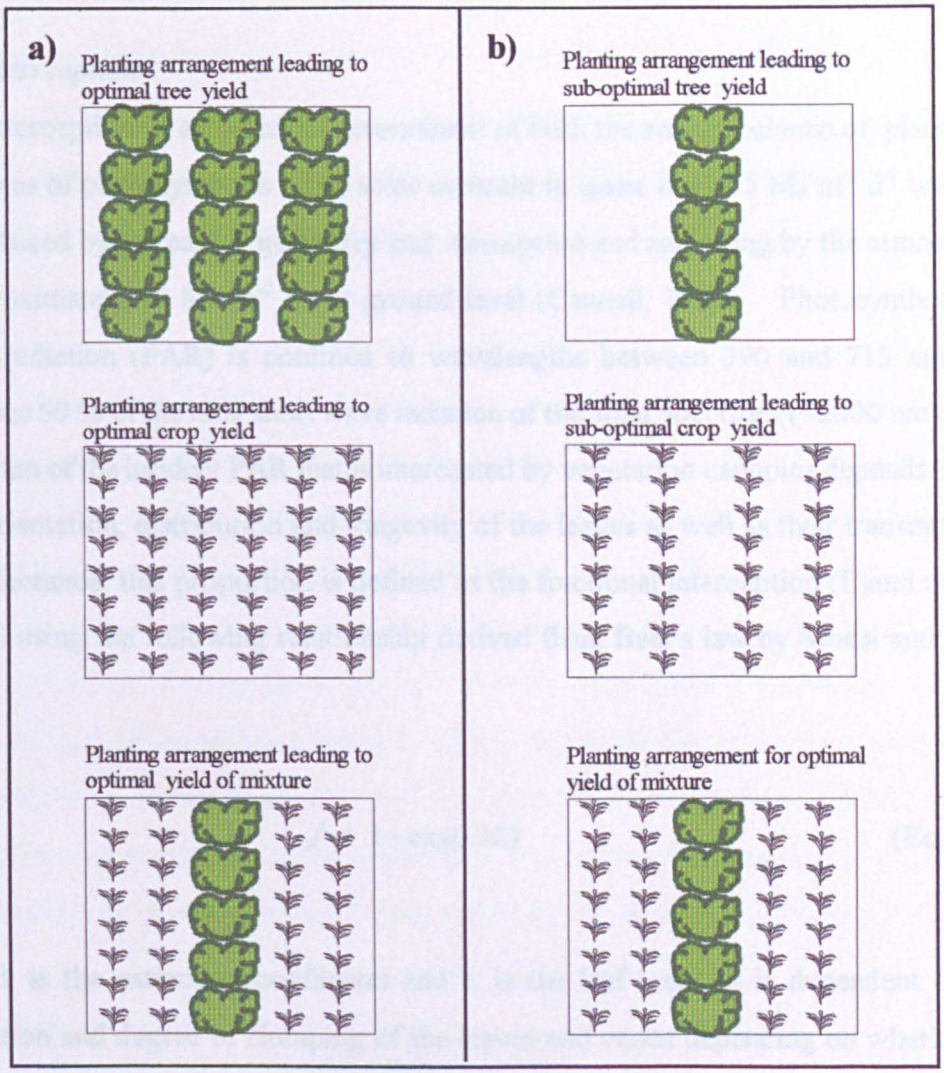

Figure 1.4 Correct (a) and incorrect (b) basis for determining the efficiency of agroforestry systems and calculating the land equivalent ratios (LER). LER is the ratio of the land area required to produce the yields of the components of a mixture to the total land area covered by the mixture (see text for further explanation).

1.4 LIGHT INTERCEPTION AND UTILISATION IN AGROFORESTRY SYSTEMS

Thorough reviews of the theory light interception and utilisation are given by Squire (1990), Monteith and Unsworth (1990) and Jones (1992) and, with particular reference to trees, by Cannell (1989). Useful reviews of measurement techniques are given by Field *et al.* (1989) and Norman and Campbell (1989), while a detailed consideration of both theory and techniques, with particular reference to agroforestry systems, is given by Ong *et al.* (1996). Keating and Carberry (1993) provided a thorough review of the principles of light capture and use in intercropping. An overview of the relevant theory, techniques and research is presented here.

Light interception

Light interception is an essential determinant of both the energy balance of plants and their rates of photosynthesis. The solar constant in space is 117.5 MJ m^{-2} d^{-1} which is then reduced by the earth's geometry and absorption and scattering by the atmosphere to approximately 10 MJ m^{-2} d^{-1} at ground level (Cannell, 1989). Photosynthetically active radiation (PAR) is confined to wavelengths between 390 and 715 nm, and comprises 50 % of the total short wave radiation of the solar spectrum (<2000 nm). The proportion of the incident PAR that is intercepted by vegetation canopies depends on the area, orientation, distribution and longevity of the leaves as well as their transmittance and reflectance: this proportion is defined as the fractional interception (f)and may be derived using the following relationship derived from Beer's law by Monsi and Saeki (1953):

$$f = 1 - \exp(-kL) \qquad \textbf{(Eq. 1.3)}$$

where k is the extinction coefficient and L is the leaf area. k is dependent on the orientation and degree of clumping of the leaves and varies depending on whether the measurements are based on the entire shortwave solar spectrum or on PAR. Squire (1990) used the relationship:

$$\ln(1-f_p) = 1.4\ln(1-f_s) \qquad \textbf{(Eq. 1.4)}$$

to convert fractional interception measurements for total shortwave solar radiation (f_s) to the equivalent PAR value (f_p). f is usually calculated as follows:

$$f = \frac{(1-f_t)}{I} \qquad \textbf{(Eq. 1.5)}$$

where I is the incident radiation above the canopy and f_t is the fraction of radiation transmitted through the canopy. Reflectance varies from 0.05 - 0.20 and is usually neglected due to the complexity of measurement (Ong *et al.*, 1996). However, as reflectance is greatest in the green and far red wavebands (Holmes, 1981), the estimation of f from PAR measurements is likely to be more accurate than corresponding estimates based on measurements of total incoming radiation because a smaller proportion of PAR is reflected.

Figure 1.5 shows the relationship between f and L for different values of k. Low k values are typical of cereals and grasses, while high k values are typical of legumes such as clover. Figure 1.6 shows the seasonal changes in f for a variety of crops; although the maximum f values differ little, the rates of canopy establishment and canopy duration show pronounced variation. Mean annual fractional interception is a function of the rate of leaf area expansion, leaf area index, k and the duration of the canopy, and varies from 0.11 for short duration sorghum (80 day duration), through 0.49 for cassava (300 day duration) to 0.88 for oil palm (Squire, 1990). Although deciduous trees may display similar variation to annual crops, conifers such as spruce and other evergreen species, may display little annual variation in either leaf area index or f (Cannell, 1989): it is this continuity of canopy cover which is responsible for the high annual f value for oil palm.

Conversion to dry matter

The rate of growth of a crop may be defined as the rate of change in its mass (W) with time (t), while the relationship between its growth rate and the capture of solar energy

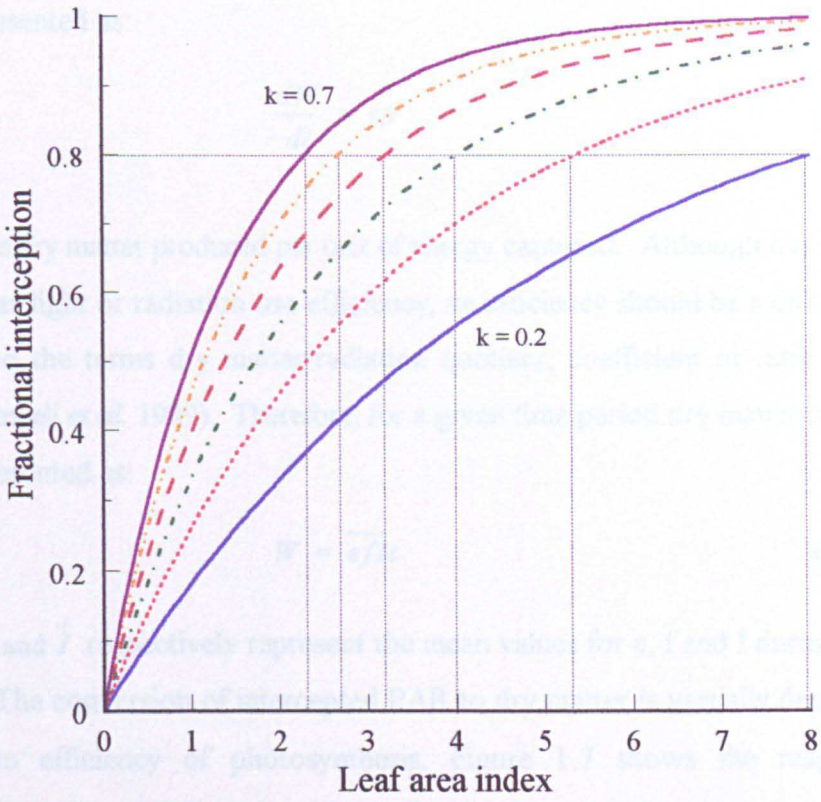

Figure 1.5 Leaf area index and fractional interception of incident solar radiation, with extinction coeficient values (k) increasing from 0.2 to 0.7 (after Cannell, 1989). Vertical lines indicate the leaf area indexes necessary to reach a fractional interception of 0.8.

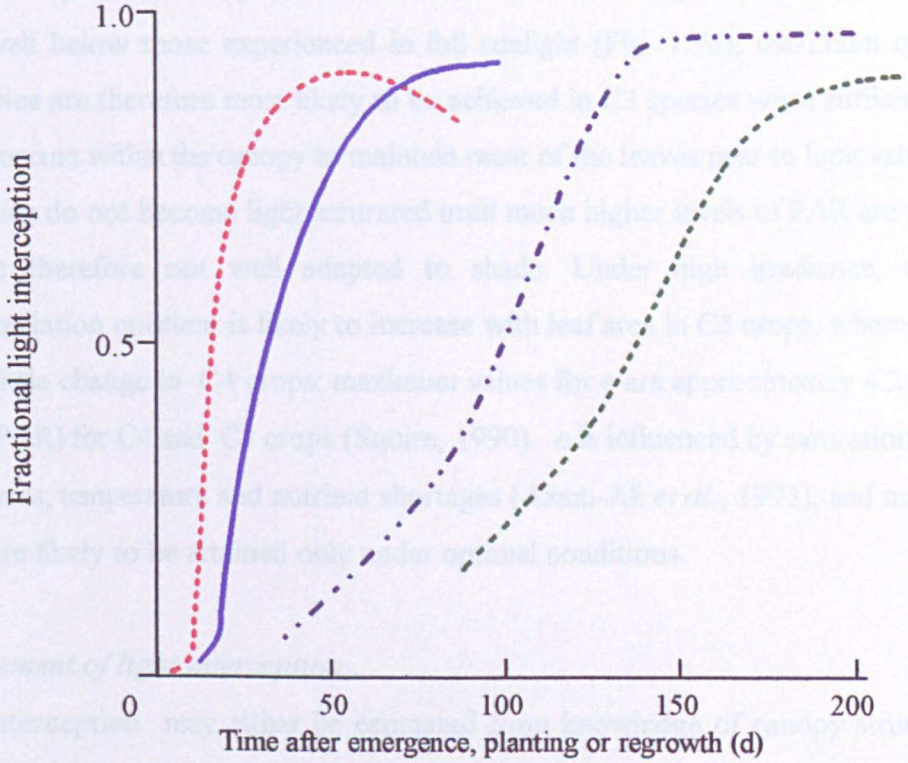

Figure 1.6 Seasonal changes of fractional interception of total solar radiation with time. For short season sorghum (- - - -), groundnut (——), cassava (— · · —) and ratoon sugar cane (- - - -) (redrawn from Squire, 1990)

may be represented as:

$$\frac{dW}{dt} = efI \qquad \textbf{(Eq. 1.6)}$$

where e is the dry matter produced per unit of energy captured. Although e is frequently referred to as light or radiation use efficiency, an efficiency should be a dimensionless ratio, and so the terms dry matter:radiation quotient, coefficient or ratio are to be preferred (Russell *et al.* 1989). Therefore, for a given time period dry matter production may be represented as:

$$W = \bar{e}\bar{f}\bar{I}t \qquad \textbf{(Eq. 1.7)}$$

where $\bar{e}$, $\bar{f}$ **and** $\bar{I}$ respectively represent the mean values for e, f and I during the time period (t). The conversion of intercepted PAR to dry matter is partially dependent on the quantum efficiency of photosynthesis. Figure 1.7 shows the responses of photosynthesis in C3 and C4 species to increasing irradiance, CO_2 concentration and leaf temperature. The quantum efficiency of C4 species is consistently greater than in C3 species except at low temperatures. C3 leaves reach full light saturation at radiation levels well below those experienced in full sunlight (Fig. 1.7a); maximum quantum efficiencies are therefore most likely to be achieved in C3 species when sufficient self-shading occurs within the canopy to maintain most of the leaves near to light saturation. C4 species do not become light saturated until much higher levels of PAR are reached and are therefore not well adapted to shade. Under high irradiance, the dry matter:radiation quotient is likely to increase with leaf area in C3 crops, whereas there will be little change in C4 crops: maximum values for e are approximately 4.2 and 2.5 g MJ^{-1} (PAR) for C4 and C3 crops (Squire, 1990). e is influenced by saturation deficit, water stress, temperature and nutrient shortages (Azam-Ali *et al.*, 1993), and maximum values are likely to be attained only under optimal conditions.

Measurement of light interception

Light interception may either be estimated from knowledge of canopy structure or measured directly. Estimation of f from canopy structure requires detailed measurements of leaf area, orientation and position, and is an extremely time-consuming and complex

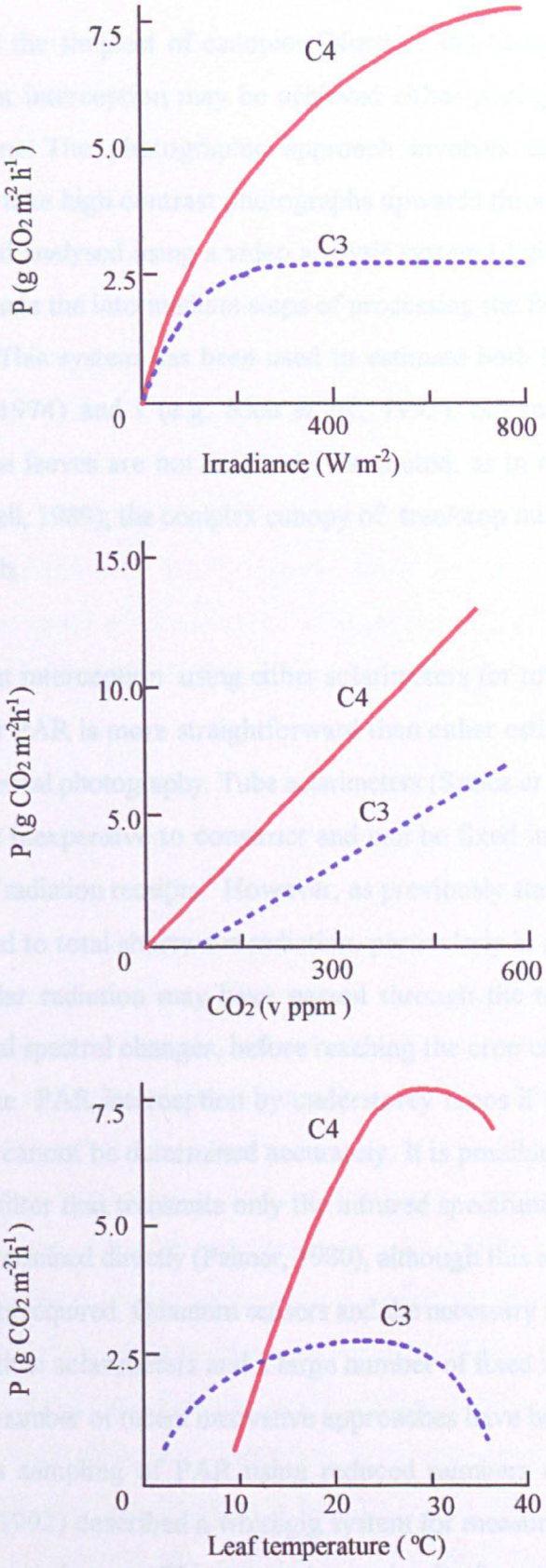

Figure 1.7 The responses of leaf photosynthesis (P) in C3 and C4 species to (a) irradiance at ambient [CO2] and optimum temperature (b) [CO2] at high irradiance, and (c) temperature at high irradiance and ambient [CO2] (redrawn from Loomis and Connor, 1992).

procedure in all but the simplest of canopies (Norman and Campbell, 1989). Direct measurement of light interception may be achieved either photographically or using various light sensors. The photographic approach involves using a camera and hemispherical lens to take high contrast photographs upwards through a canopy, which are then digitised and analysed using a video analysis system (digital cameras are now available which eliminate the intermediate steps of processing the film and digitising the images obtained). This system has been used to estimate both leaf area index (e.g. Bonhomme *et al.*, 1974) and f (e.g. Rich *et al.*, 1993), but may require complex calibration where the leaves are not randomly distributed, as in row-planted systems (Norman and Campbell, 1989); the complex canopy of tree/crop mixtures does not lend itself to this approach.

Measurement of light interception using either solarimeters for total solar radiation or quantum sensors for PAR is more straightforward than either estimation from canopy structure or hemispherical photography. Tube solarimeters (Szeicz *et al.* 1964; Green and Deuchar, 1985) are inexpensive to construct and can be fixed in position to permit diurnal integration of radiation receipts. However, as previously stated, measurement of PAR is to be preferred to total shortwave radiation, particularly in agroforestry systems where incoming solar radiation may have passed through the tree canopy, thereby undergoing substantial spectral changes, before reaching the crop canopy; it is therefore difficult to determine PAR interception by understorey crops if the quantity of PAR incident on the crop cannot be determined accurately. It is possible to pair solarimeters with and without a filter that transmits only the infrared spectrum, thus allowing PAR interception to be determined directly (Palmer, 1980), although this approach doubles the number of instruments required. Quantum sensors and the necessary recording equipment are more expensive than solarimeters and a large number of fixed sensors is an unlikely option. However, a number of recent innovative approaches have been developed which allow instantaneous sampling of PAR using reduced numbers of quantum sensors. McNaughton *et al.* (1992) described a whirligig system for measuring net radiation and PAR absorption by a single tree. This system has a circular frame with an arrangement of radiometers and PAR sensors surrounding the tree, with the whole system being continually rotated to provide an integrated sphere of measurements. The whirligig

provides the most accurate method of determining radiation interception by trees, but is limited in its application to isolated trees. Matthews and Saffell (1987) describe a "mouse" which comprised a 1.5 m long metal tube with holes drilled at 2 cm intervals, through which a quantum sensor is manually pulled. The sensor was referenced against another located above the tree or crop row to allow the measurement of PAR interception along transects across crop rows and tree alleys. The "mouse" has obvious benefits, but is time-consuming if large numbers of transects are required. The Sunfleck Ceptometer (Delta-T Devices, UK) consists of a 80 cm long probe, with 80 quantum sensors evenly spaced along its length. This instrument allows an integrated instantaneous measurement of PAR to be made along transects, while paired measurements from above and below canopy allow fractional interception to be determined. Ease and speed of sampling permit large numbers of measurements to be completed within a short period. Although this approach cannot provide the level of detail of the whirligig or mouse, it nevertheless allows the determination of PAR interception by both trees and crops with reasonable accuracy; this instrument was employed in studies of both the agroforestry systems described in this thesis.

Light capture and utilisation in agroforestry systems

There have been numerous studies of light capture and utilisation in sole crops and intercrops, but research into these processes in agroforestry systems is more limited. There is vast diversity of intercrop canopy structures, and these often change markedly as the growing season or annual cycle progress (Keating and Carberry, 1993) Essentially, tree/crop mixtures have much in common with crop/crop mixtures. The diversity of intercrop canopies and the complexity of measuring light capture and utilisation in such systems have inspired a large number of simulation models for intercrops (e.g. Sinoquet and Caldwell, 1995), mixed pastures (e.g. Rimmington, 1984, 1985; Sinoquet *et al.*, 1990), alley cropping (Nygren and Jiménez, 1993), intercrops and agroforestry (Wallace, 1995) and crops and weeds (Wiles and Wilkerson, 1991). Sinoquet and Caldwell (1995) went as far as to suggest that "simulation is therefore the only practical way to look into light competition." However, as canopy structure and development in mixed communities depends on the extent of competition for below-ground resources as well as above-ground for light, there is a great need for holistic field research to establish the

relative importance of these processes and the resulting interactions.

The desired result of an intercrop or agroforestry system is usually enhanced productivity, which must result from an increase in either light capture or in the dry matter:radiation coefficient. Increases in resource capture may result from either temporal or spatial complementarity. Short season cereals such as sorghum (Fig. 1.6), with their rapid leaf area development, are well adapted to short growing seasons but will under-exploit resources under conditions where the growing season is longer (Keating and Carberry, 1993). Under longer growing seasons, long duration crops with comparatively slow rates of leaf development will under-exploit resources early in the season. Figure 1.8 shows that the combination of a short-season cereal with a long duration pigeonpea increased fractional interception in the intercrop relative to either sole crop, except for a period after removal of the maize from the intercrop (Sivakumar and Virmani, 1980). Similar results have been recorded for other cereals, although Keating and Carberry (1993) emphasised the need to compare long duration intercrops with serial sole crops wherever appropriate. Figure 1.9 shows the more rapid increase in the fractional interception of a combined tree/crop canopy relative to either sole crop or tree, effectively demonstrating spatial complementarity. Spatial complementarity is only likely where the optimal sole crop density does not result in full light interception due to limitations of water or nutrient availability (Keating and Carberry, 1993).

Intercropping of beans and maize is common practice in East Africa (Tyndall, 1993) and the potential for improvements in productivity due to increases in the dry matter:radiation coefficient have previously been suggested for such combinations of tall C4 and short C3 crops (Trenbath, 1986). The tall C4 species, with its near-vertical leaves and low k value, allows effective light penetration to the understorey C3 crop and a correspondingly good distribution of light throughout the mixed canopy; the partially shaded bean canopy is therefore maintained at light levels below saturation but still receives sufficient radiation to support growth (Fig. 1.7 a). Improvements in light capture and/or utilisation in agroforestry are therefore dependent on the manipulation of tree and crop growth rates, canopy durations, canopy structures and improvements in quantum efficiency under lowered irradiances.

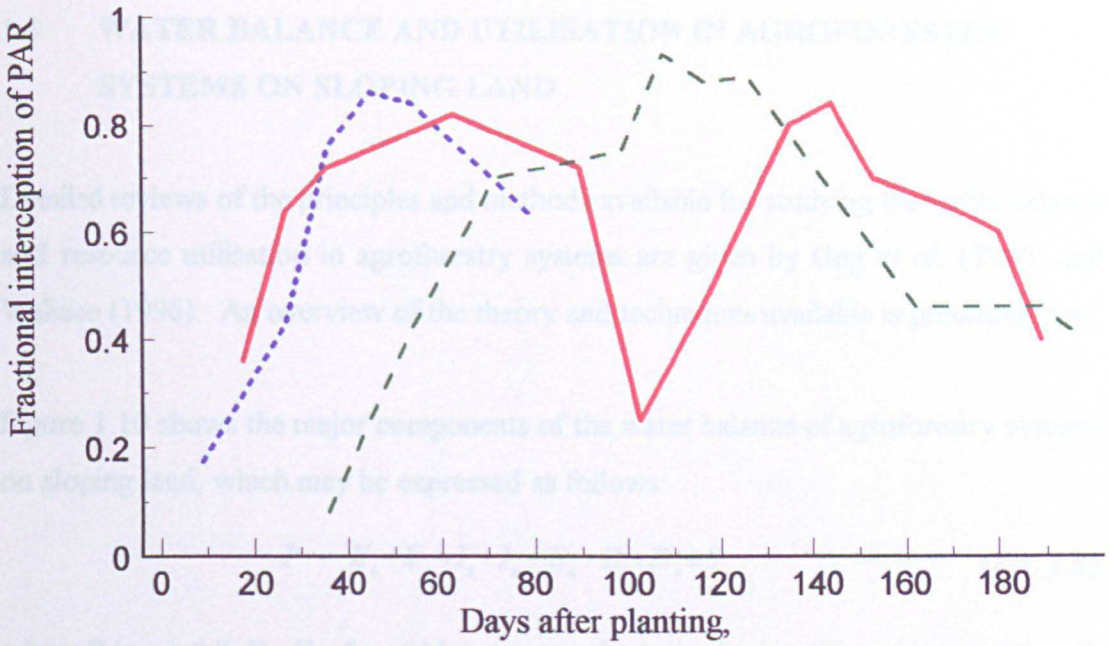

Figure 1.8 Fractional interception of photosynthetically active radiation (PAR) over in time in sole maize (·····), sole pigeonpea (– – –) and a maize/pigeonpea intercrop (———) (after Sivakumar and Virmani, 1980).

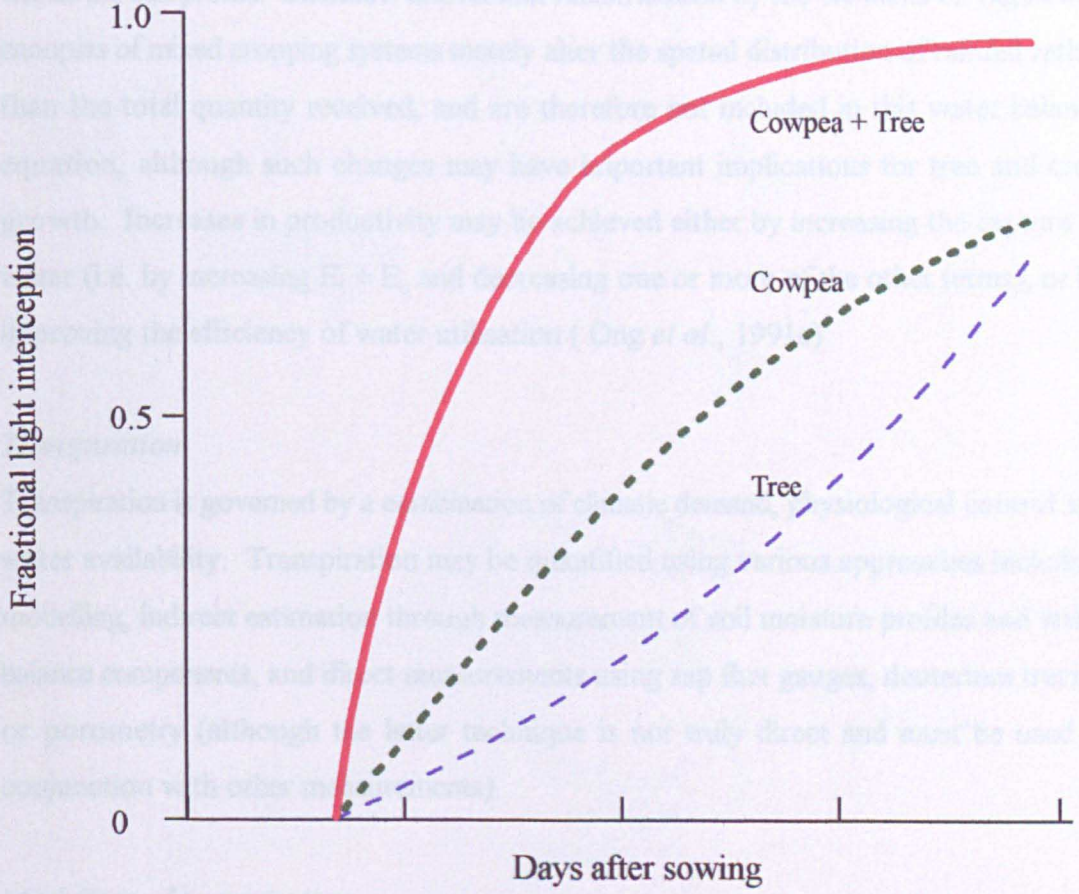

Figure 1.9 Fractional interception of radiation by sole cowpea, sole trees (*Senna spectabilis*) and a mixture of trees and crop (redrawn from Ong *et al.*, 1996).

1.5 WATER BALANCE AND UTILISATION IN AGROFORESTRY SYSTEMS ON SLOPING LAND

Detailed reviews of the principles and methods available for studying the water balance and resource utilisation in agroforestry systems are given by Ong *et al.* (1996) and Wallace (1996). An overview of the theory and techniques available is presented here.

Figure 1.10 shows the major components of the water balance of agroforestry systems on sloping land, which may be expressed as follows:

$$P = E_t + E_c + I_t + I_c + E_s + R + D_r \pm S \qquad \textbf{(Eq. 1.8)}$$

where P is rainfall, E_t, E_c, I_t, and I_c represent the transpiration (E) and interception (I) losses by the trees (t) and crops (c), E_s indicates soil evaporation, R denotes runoff, D_r is drainage (deep percolation and lateral flow), and S is the change in water storage within the soil profile. Stemflow and rainfall redistribution by the elements of vegetation canopies of mixed cropping systems merely alter the spatial distribution of rainfall rather than the total quantity received, and are therefore not included in this water balance equation, although such changes may have important implications for tree and crop growth. Increases in productivity may be achieved either by increasing the capture of water (i.e. by increasing $E_t + E_c$ and decreasing one or more of the other terms), or by improving the efficiency of water utilisation (Ong *et al.*, 1991a).

Transpiration

Transpiration is governed by a combination of climatic demand, physiological control and water availability. Transpiration may be quantified using various approaches including modelling, indirect estimation through measurement of soil moisture profiles and water balance components, and direct measurements using sap flux gauges, deuterium tracing or porometry (although the latter technique is not truly direct and must be used in conjunction with other measurements).

Modelling of transpiration

The Penman-Monteith equation (Monteith, 1965) marked a landmark in the

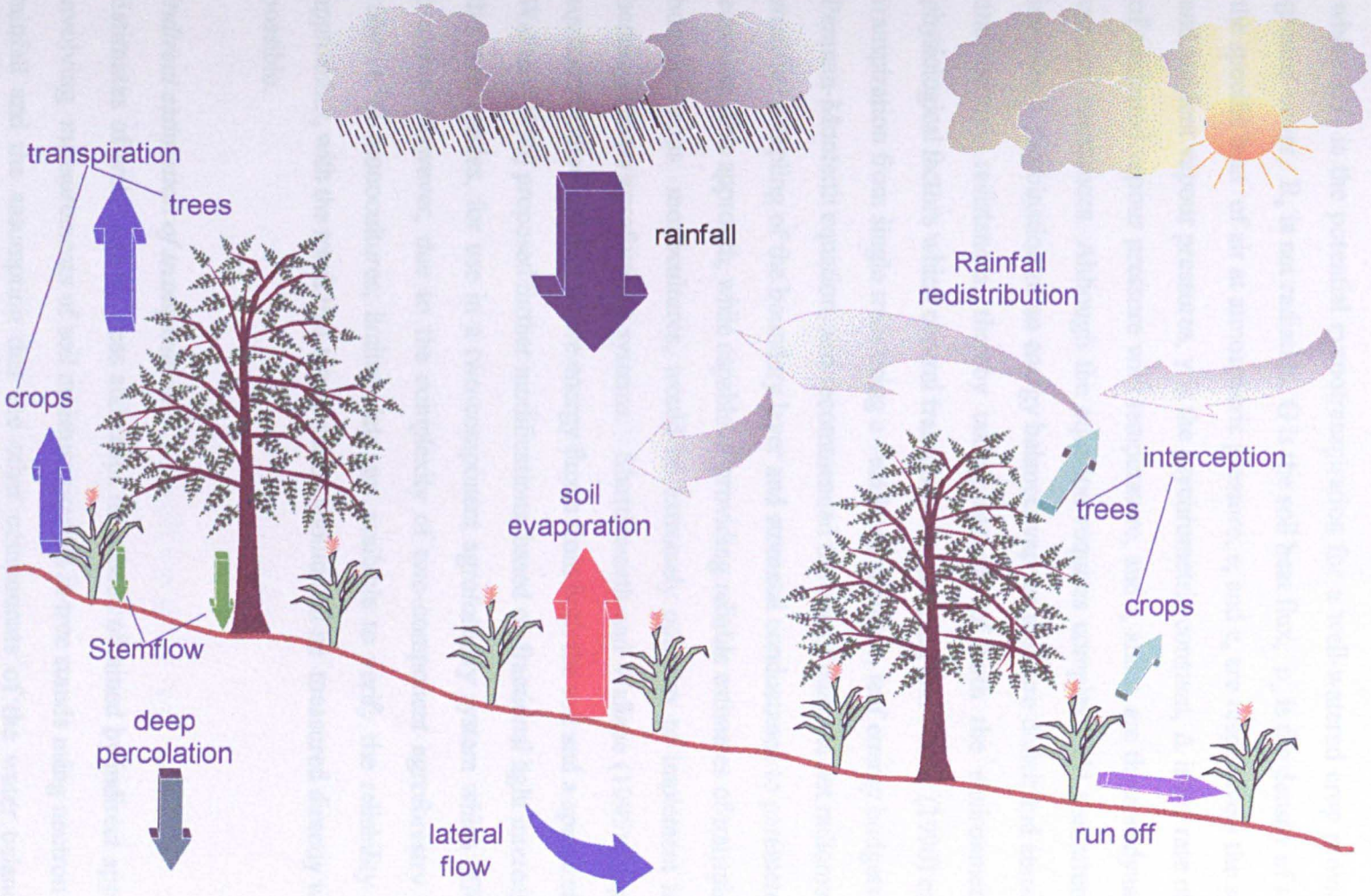

Figure 1.10 Components of the water balance of an agroforestry system on sloping land

understanding of evapotranspiration. This takes the form:

$$ET_o = \frac{[\Delta(R_n - G) + \rho_a C_p (e_s - e_a)/r_a]}{[(\Delta + \gamma)(1 + r_c/r_a)]} \qquad \textbf{(Eq. 1.9)}$$

where ET_0 is the potential evapotranspiration for a well-watered crop providing full ground-cover, R_n is net radiation, G is the soil heat flux, ρ_a is the density of air, C_p is the specific heat of air at atmospheric pressure, e_s and e_a are respectively the saturated and ambient vapour pressures, γ is the psychrometric constant, Δ is the rate of change of saturated vapour pressure with temperature, and r_a and r_c are the aerodynamic and canopy resistances. Although the equation requires complex field measurements, it involves a combination of an energy balance, vapour pressure deficit and aerodynamic and canopy resistances, thereby taking account of both the environmental and physiological factors which control transpiration. Leuning and Foster (1990) estimated transpiration from single trees using a ventilated chamber, leaf energy budgets and the Penman-Monteith equation, and recommended the use of multiple net radiometers and stratified sampling of the boundary layer and stomatal conductance to parameterise the equation. This approach, while capable of providing reliable estimates of transpiration in homogeneous monocultures, would be extremely complex to implement in highly heterogeneous agroforestry systems. Shuttleworth and Wallace (1995) adapted this equation to allow for interactive energy fluxes from both the soil and a sparse crop, and Wallace (1995) proposed further modifications, based on fractional light interception by the two species, for use in a two-component agroforestry system which offer some promise. However, due to the complexity of two-component agroforestry systems relative to monocultures, limited data are available to verify the reliability of such approaches, with the result that transpiration should still be measured directly wherever possible.

Indirect estimation of transpiration

Estimates of water use by trees and crops have been obtained by indirect approaches involving measurements of soil moisture profiles in tree stands using neutron probes, rainfall and the assumption that the other components of the water balance were negligible (e.g. Eastham, 1988); similar methods have been used with crops (e.g. Cooper

et al., 1983). Such water balance approaches are valid for single-component systems but do not allow the partitioning of water use between the components of mixed cropping systems; for example, in a study of water use by monocropped and intercropped cowpea and sorghum, Morris *et al.* (1990) were only able to conclude that the quantity of water removed from the soil profile under the intercrop was lower than in the sole cowpea and greater than in the sole sorghum, but were unable to partition water use between the component species.

Measurement of transpiration

Several methods are currently employed to measure transpiration under field conditions: including whole plant chambers, isotopic techniques, porometric measurements of stomatal resistance, and sap flux techniques. The chamber approach involves enclosing the plant in a cuvette and measuring the fluxes of water vapour (and CO_2 if required), and has been adapted for use with large trees (Goulden and Field, 1994); however, this approach alters the microclimatic conditions experienced by the enclosed plant and lacks portability.

Isotopic techniques involve using a radioactive tracer or non-radioactive isotope such as deuterium (Calder *et al.* 1992) and require a known quantity of the tracer to be injected in to the stem. Plastic bags are placed over samples leaves, transpirant is collected every day over the following few days and the proportion of deuterium in the transpirant is analysed by mass spectrometry. Transpiration rate is calculated from the area under the deuterium concentration timecourse (Wallace, 1996). There are certain disadvantages to this method as it only provides integrated estimates over periods of several days, requires access to a mass spectrometer and involves difficulty in interpreting the results obtained.

Porometry provides a measure of stomatal resistance (r_s), rather than a direct determination of transpiration, and relies on concurrent measurements of boundary layer resistance (r_a), the vapour concentration difference between leaf and atmosphere ($\delta\chi$) and leaf area index (L). In order to account for variation within the canopy, sampling is usually stratified for different layers and transpiration (E_t) from each layer is calculated

as:

$$E_t = \frac{[\delta\chi]L}{(r_s + r_a)} \qquad \textbf{(Eq. 1.10)}$$

Transpiration (E_t) is then summed for all layers to obtain a value for the canopy (Azam-Ali, 1983). This method has been used for sole crops (Black *et al.*, 1983; Azam-Ali, 1983; Wallace *et al.*, 1993), the individual components of intercrops (Azam-Ali *et al.* 1990) and a rainforest (Roberts *et al.*, 1993). Sampling intensity must be adjusted according to the complexity of the canopy structure; Azam-Ali (1983) used three sampling layers for a millet canopy, whereas Roberts *et al.* (1993) employed six layers for the more heterogeneous rainforest canopy. Ong *et al.* (1996) suggested that a major disadvantage of the porometric approach for measurement of transpiration is the high sampling intensity required, combined with the discontinuous nature of the values obtained and the sap flux approach was therefore preferred in the present study.

Sap flux may be measured using three fundamentally different techniques, namely the magnetohydrodynamic, the heat pulse and the heat balance. In the magnetohydrodynamic method of Sheriff (1972), a stem is subjected to a magnetic field, applied perpendicular to sap flow, and the induced voltage is measured using platinum electrodes placed close to the xylem. Whilst this is an elegant method, it has not been field-tested and most subsequent development work has concentrated on the heat pulse and heat balance approaches.

Huber (1932) developed the heat pulse method, which has been subsequently modified by several workers (cf. Swanson, 1994). The principle remains the same in that a pulse of heat with a duration of a few seconds is applied to the stem and the velocity of transport of this pulse downstream along the stem is measured. Sap flux velocity is then calculated from the velocity of the heat pulse. The method can be used without calibration on species in which the wood is thermally homogeneous, but in thermally heterogeneous species sap flow may be overestimated by up to 7 times (Sabatti *et al.*, 1993). Green and Clothier (1988) described two methods for testing the technique. Their laboratory method involves forcing water through an excised stem segment, to which

heat pulse equipment was connected; the water passing through the stem was collected and weighed to give a measure of sap flux. The field method involved placing the base of an excised tree, again with heat pulse equipment attached, in a large container of water, which was then sealed so that all water loss occurred as sap flux. Despite the problems with thermally heterogeneous species, the heat pulse method is capable of providing reasonable estimates of transpiration when applied carefully (e.g. Cohen *et al.*, 1981). Indeed, this approach is now being widely used at ICRAF for measurements of sap flux through the stems and roots of tree species (C. K. Ong, pers. comm.).

The heat balance method devised by Vieweg and Ziegler (1960) used a flexible electrical heater wrapped around the stem to supply heat to the enclosed stem segment; heat differentials were measured at positions up and downstream of the heater. The stems were insulated with polystyrene and aluminium foil to minimise radial exchange of heat. There are two variants to this approach; in one a constant input of heat is applied (Sakuratani, 1981, 1984; Baker and van Bavel, 1987), while in the other the heater is maintained at a fixed temperature increment above the stem (Ishida *et al.*, 1991). In the first method, the constant input of heat is balanced by heat fluxes away from the heated stem segment (by conductive fluxes through the stem and surrounding insulation and mass transfer in the sap); temperature is measured outside the insulation and in the stem above and below the heater to quantify these fluxes. In the second method, the heat input increases with sap flux and radial heat losses through the insulation are assumed to be zero. This approach is technically simpler and less expensive and is thus suitable for wide-scale application in field experiments; this approach was therefore adopted in the present study (Section 4.7 provides a full description of the technique). Cermak *et al.* (1984) employed a modified version of the heat balance approach for stems over 120 mm in diameter, in which heat was applied only to a sector of the stem circumference rather than evenly to the entire circumference of the stem. Although this method is vulnerable to spatial heterogeneity within the stem, it is more practical for large trees than the unmodified stem heat balance gauge because of its smaller power requirements for the heater input. Heat balance gauges have now been widely applied to woody stems (e.g. Steinberg *et al.* 1987), herbaceous plants (e.g Baker and van Bavel, 1987), coniferous saplings (Groot and King, 1992), large forest trees (Kelliher *et al.*, 1992) and to trees and

crops in agroforestry situations (Marshall *et al.*, 1994; Howard *et al.*, 1995). Commercial gauges are available in a range of sizes for stems up to 125 mm in diameter (Dynamax Dynagauge, USA) with reported accuracy of 10 % (Ong *et al.*, 1996).

Water use and the dry matter:transpired water ratio

The relationship between water use and dry matter production has been discussed at length by several authors (e.g. Ong, *et al.* 1996; Squire, 1990) and a brief overview is presented here. The weight of dry matter in a stand (W) is related to accumulated transpired water as follows:

$$W = e_w \Sigma E_t \qquad \textbf{(Eq. 1.11)}$$

where e_w is the ratio of dry matter:transpired water, sometimes referred to as the water use efficiency. Water use efficiency can also be calculated as the quantity of dry matter produced per unit of water applied, or per unit of total evapotransporation and, sometimes has been referred to as the transpiration efficiency (Morris and Garrity, 1993). W tends to increase in a near-linear fashion with $\sum E_t$; this relationship is based on the principles of gas exchange, since water is lost through stomata (E_t) in order to allow the penetration of carbon dioxide from the atmosphere to the chloroplast (Squire, 1990). For an individual leaf, e_w may be represented as:

$$e_w = \frac{A_l}{E_l} \qquad \textbf{(Eq. 1.12)}$$

where A_l is the net uptake of carbon dioxide and E_l is the loss of water from the same leaf. A_l may be expressed as:

$$A_l = \frac{(c_a - c_i)}{r_c} \qquad \textbf{(Eq. 1.13)}$$

where c_a and c_i are the concentrations of carbon dioxide in the atmosphere and the intercellular spaces within the leaf, and r_c is the sum of the boundary layer and epidermal resistances to the diffusion of carbon dioxide. Similarly, E_l may be expressed as:

$$E_l = \frac{(v_a - v_i)}{r_w} \qquad \textbf{(Eq. 1.14)}$$

where v_a and v_i are the concentrations of water vapour in the atmosphere and in the intercellular spaces within the leaf. r_w is the sum of the boundary layer and epidermal resistances to the diffusion of water vapour. Combining equations 1.12, 1.13 and 1.14 gives:

$$e_w = \frac{(c_a - c_i)}{\beta(v_i - v_a)} \qquad \textbf{(Eq. 1.15)}$$

where β is the ratio of the diffusion resistances to carbon dioxide and water vapour (effectively constant at approximately 1.6:1; Ong *et al.*, 1996). The difference between the internal and external concentrations of water vapour is much more variable than that for carbon dioxide since v_a fluctuates with atmospheric temperature and humidity, whereas c_a is much more constant. Brown *et al.* (1987) stated that, when leaf and air temperatures are identical, then $(v_i - v_a)$ corresponds to the saturation vapour pressure deficit (D). Furthermore e_w is inversely proportional to D and e_wD is conservative (Squire, 1990) except under drought or nutrient deficient conditions (Ong *et al.*, 1987, 1996). Squire (1990) collated several reported values of e_w and e_wD for pearl millet and groundnut, and found that, whereas the e_w values showed more than threefold variation in both species, e_wD varied by only 25 % of the mean; the e_wD values recorded for the C4 millet were more than double those for the C3 groundnut. The greater water use "efficiency" of C4 relative to C3 species was also shown by Loomis and Connor (1992), who calculated values of e_w corrected for differences in D for a wide range of species; the values for C4 species were consistently more than twice those for C3 species.

In agroforestry systems where the crop is sheltered by trees which act as a windbreak, atmospheric temperature and humidity are both likely to be increased (Brennar *et al.*, 1995). Since D depends on both temperature and vapour pressure, its value under sheltered conditions may be either larger or smaller than in the open. Monteith *et al.* (1991) reported little difference between D values within and outside a *L. leucocephala*/millet alley cropping system. However, these authors did suggest that the six-fold reductions in D values that have been observed in closed forests indicate that there are large potential gains to be had from reductions in D values in agroforestry systems, and that this was an issue worthy of further research.

Complementarity or competition in water use: increased resource capture

If more dry matter is to be produced, then either more water must be captured or the dry matter:water use ratio must be increased. Morris and Garrity (1993) suggested that an important potential benefit of intercropping was an increase in the proportion of evapotranspiration that occurs as transpiration. This effect may result from more rapid canopy expansion early in the season, thereby reducing soil evaporation and increasing transpiration, a higher combined leaf area in the intercrop (e.g. Fig. 1.9), or longer canopy duration (e.g. Fig. 1.8).

Huxley (1983) suggested that the different rooting depths of trees and crops would increase resource capture without introducing intense below-ground competition. However, subsequent research, mainly in alley-cropping systems, has shown that differences in rooting depth are not invariably found, and that competition for water, rather than complementarity in its use, may result from combining fast-growing trees (e.g. *Leucaena leucocephala*) with annual crops in a single system (Ong *et al.*, 1991b; Daniel *et al.*, 1991). Ong *et al.* (1996) suggested that the maximum rooting depth in crops ranges from 70 cm for most short duration cereals and legumes to 1.5-3.0 m for longer duration crop varieties. Tree roots display enormous variability in depth, lateral extent and density, and reports include a mature *Eucalyptus* tree with an estimated rooting depth of 60 m (Jennings, 1971). Stone and Kalisz (1991) cited 30 cases where the roots of various tree species gained contact with water tables ranging from 1.5-35 m in depth. However, roots can also exhibit extensive lateral spread, such as a 4 m tall

Western Australian Christmas tree, *Nuytsia floribunda* (Labill.) R.Br., in which the lateral roots extended over 50 m from the trunk (Hocking, 1980) and a three year old *Tournefortia argentea* Linn. f. tree with a lateral root radius of 18 m (Billings, 1964).

The presence of deep roots alone does not guarantee complementarity in water use, and knowledge of root distribution is of limited value in the absence of corresponding information concerning water and nutrient uptake (Ong and Khan, 1993). Ong and Khan (1993) measured sap flux in the roots of *Croton megalocarpus* using heat balance gauges and demonstrated an approximate doubling of sap flux in the primary root when several lateral roots were severed. This compensation occurred in well-watered soil when total sap flux was probably demand-limited rather than supply-limited. Several approaches have been used to study the uptake of water by roots. These include combinations of soil moisture depletion with information on root distribution or sap flux through the trunk (Ong *et al.*, 1991b; Daniel *et al.*, 1991; Howard *et al.*, 1995), analysis of xylem sap for stable isotopes (Dawson and Ehleringer, 1991), and the use of heat balance gauges to measure sap flux through roots directly (Ong and Khan, 1993). While these methods all have their merits, they do not allow the extent of tree/crop complementarity in water use to be established directly.

A method for examining the extent of below-ground complementarity between trees and crops and results obtained in an agroforestry system containing grevillea and cowpea are presented in Sections 4.8 and 7.3 of this thesis. Heat balance gauges (Ishida *et al.*, 1991; Khan and Ong, 1995; Lott *et al.*, 1996) were used to measure sap flux in grevillea trees before and after removing the soil within the crop rooting zone to a depth of 60 cm from around the base of the trees. The excavation of the crop rooting zone prevented any water uptake except from beneath this zone. Sap flux was measured for grevillea trees before and after pruning to establish whether water uptake was demand or supply-limited. The degree of below-ground complementarity could therefore be established by determining the proportion of the total sap flux through the trees which was drawn from beneath the crop rooting zone.

Soil evaporation

Cooper *et al.* (1983) reported that soil evaporation (e_s) may account for approximately 60 % of rainfall in semi-arid and arid areas, while Jones (1992) stated that e_s may comprise 50 % of rainfall until a leaf area index of 2 is reached. Indirect estimates of e_s can be obtained using various techniques, including neutron probe studies to establish seasonal changes in soil moisture profiles. Wallace (1996) summarised more direct approaches for measuring e_s, including the Bowen-ratio micro-meteorological method(Ashktorab *et al.*, 1989), radio-isotope techniques (Taupin *et al.*, 1991) and a soil porometer (Nobel and Geller, 1987). However, microlysimeters provide a direct and cost-effective method for quantifying e_s and permit the extensive simultaneous replication required in spatially heterogeneous agroforestry systems. Daamen *et al.* (1993) discussed the methodological aspects involved in using microlysimeters to measure e_s in some detail.

Ritchie (1972) developed an empirical two-stage equation to describe soil evaporation:

$$\Sigma\, e_s = U + \alpha\sqrt{(t-t_1)} \qquad \textbf{(Eq. 1.11)}$$

where U is the quantity of water lost during first stage evaporation immediately following rainfall, α is the second stage constant, t is the time since the last rain (days) and t_1 is the duration of first stage evaporation. This equation is simple to apply, with U and α being determined empirically for a given site, and has been reported to be reasonably accurate over several drying cycles (within -4 to +13 % of measured e_s; Daamen, 1991). For these reasons, the Ritchie equation was parameterised using values measured with micro-lysimeters and used to calculate seasonal e_s values for the Machakos site; the method and results obtained are described in Sections 4.9 and 7.5.

Runoff

Runoff generally occurs when rainfall intensity exceeds the rate of infiltration into the soil and generally increase with the steepness of slope (Kiepe, 1995). Approximately 40 % of rainfall in the tropics falls at rates in excess of 25 mm h^{-1}, compared with only 5 % in the temperate zone (Davis and Payne, 1988), thus greatly increasing the potential for

runoff. Kiepe (1995) measured runoff over six rainy seasons on a 14 % slope at ICRAF's Machakos field station . A number of treatments were used, including sole maize, maize plus a *Cassia siamea* (Lam.) hedgerow (with a 0.25 intra-row and 4 m inter-row spacing), maize plus cassia mulch and maize with both hedgerows and mulch. Kiepe found that runoff was decreased by 60 % in the mulch treatment, >75 % in the hedgerow treatment and >85 % in the hedgerow plus mulch treatment. These decreases in runoff were attributed to an increased rate of infiltration under the hedgerows and physical barrier provided by the hedgerow and mulch. Although these reductions were substantial, runoff in the control accounted for less than 5 % of the rainfall over the six seasons examined. Lal (1989) found less runoff when sole crops were grown on untilled land than when crops were grown with leucaena or *Gliricidia sepium* hedgerows, indicating that land preparation may outweigh the choice of system.

Interception

In much the same way that light is intercepted by overstorey canopies, the interception of rainfall by the trees in agroforestry systems reduces its availability to understorey crops. Interception is likely to be greatest where rainfall occurs most frequently as light showers or low intensity events rather than as high intensity, short duration storms (Leyton, 1983; Calder, 1986). In a review of the available literature, Bussiere (1995) stated that this represents the first stage of water partitioning between the components of intercropping systems. An important consideration is that the rate of evaporation from wet tree canopies is likely to be far greater than that from shorter vegetation due to the surface roughness of exposed canopies and the correspondingly lower boundary layer resistance (Calder, 1992b); this is likely to be especially true in agroforestry systems where the trees are more isolated and exposed than in a forest environment. Thus, Monteith *et al.* (1991) recorded interception losses of 20 % due to the presence of leucaena in a leucaena/millet agroforestry system. In a separate trial, in which sole leucaena was grown to a height of 5 m at densities of between 400 and 10000 trees ha^{-1}, rainfall interception increased from 10 % at the lowest tree density to 40% at the highest.

Gash (1995) proposed a modification of an earlier model to allow the estimation of

interception losses in sparse forest canopies; in the revised model the throughfall fraction, stemflow, stem storage, canopy storage capacity and evaporation rates must be established or estimated. Teklehaimanot and Jarvis (1991) determined canopy storage capacity and subsequent evaporation by suspending excised spruce trees from a load cell and spraying them with water. Crown storage was taken as the weight of water retained on the tree after drainage had ceased, from which canopy storage was calculated (storage per unit ground area); the ensuing weight loss was then used to determine the rate of evaporation. These workers reported that the boundary layer conductances of the trees increased greatly with decreasing tree density; this has obvious implications for agroforestry systems with moderate tree densities.

1.6 NUTRIENTS

Two of the basic assumptions concerning the potential advantages of agroforestry are the transfer of nitrogen from leguminous trees to associated crops and the cycling of nutrients from deep soil horizons (Young, 1991). Direct transfer of nitrogen has now been shown to be of little significance (Giller and Wilson, 1991) although root turnover, in which root death in the legume releases nutrient into the soil, may provide some benefit to associated non-leguminous crops (Ong, 1995). A study of nitrogen transfer from the leguminous leucaena to a sorghum intercrop growing on nitrogen-poor soil showed that less than 1 % of the nitrogen budget of leucaena was transferred to the sorghum (Avery and Rhodes, 1990). The extent to which trees can improve nutrient cycling is still largely unknown, fallows planted with *Sesbania sesban* have shown significant improvements in subsequent maize yields (ICRAF, 1992, 1993).

Heineman (1995) compared maize and tree yields in 12 alley cropping treatments, containing five provenances of *Leucaena leucocephala*, one of *L. coliinsi* and six of *Gliricidia sepium*. In each treatment, the trees were pruned and the leaf material returned to the plot at approximately two-monthly intervals, with a view to enhancing soil

properties. As maize yield was positively correlated with the quantity of mulch applied, Heineman concluded that these systems were worthwhile in the humid tropics where light and water are not the primary limiting factors for growth. However, it is possible that the positive correlation obtained was due to variation in the background fertility of the plots leading to improvements in crop and tree growth (hence greater mulch production); thus the correlation of crop growth and the quantity of mulch applied may have been artefacts of fertility differences between plots. Even if this was not the case, the lack of valid sole maize and tree controls in this experiment means that there is insufficient information to judge unequivocally whether this form of alley cropping is worthwhile; for example, overall maize yield might have been increased still further by sequential sole cropping.

In a review of ICRAF's alley cropping research, Akyeampong *et al.* (1992) reported that the addition of 1 t ha^{-1} of leucaena mulch produced a response similar to 2-4 kg ha^{-1} of inorganic nitrogen. When comparing the positive effect of mulching with competition from the hedgerows, they found that the overall effect of alley cropping might be positive in one season and negative in the next, with substantial variation between sites and species. Lulanda and Hall (1990) demonstrated that substantial quantities of nutrients were removed by harvesting leucaena for fodder, amounting to 88, 48, 20, 8 and 5 kg ha^{-1} $year^{-1}$ for nitrogen, potassium, calcium, magnesium and phosphorus respectively. Any system where significant quantities of plant products are removed during the cropping or annual cycles will result in the removal of nutrients, and agroforestry is no different from sole cropping or forestry in this respect.

1.7 MAIZE AND COWPEA

Maize

Maize or corn (*Zea mays*) is a member of the grass family (*Gramineae*), was originally cultivated by the indigenous North Americans and introduced to Europe by Columbus,

and is now grown extensively throughout the warm temperate and tropical zones. It is the third most important crop after wheat and rice in terms land area and production, with an estimated 127 million hectares under maize cultivation in 1988, yielding 349 million tonnes of dry matter (FAO Production Year Book, 1988). This represents an area more than twice the size of Kenya and approximately 12 % of all crop land. These three cereals, together with barley, account for more than half of the total world crop production (Loomis and Connor, 1992). The dominance of cereals results from their broad environmental range as annual generalists, their high digestibility, and good nutritional value with 8-14 % of the grain consisting of protein and 60-80 % of carbohydrates; cereals are also easily transported and stored (Loomis and Connor, 1992). Maize is consumed in an enormous variety of ways including boiled or grilled on the cob, stewed off the cob with beans, coarse-ground and steamed as polenta, or ground into flour and made into unleavened bread, biscuits, or thick porridge, such as the East African ugali.

Yield improvement

Maize yields in the USA have increased from 2.3 to over 6 t ha^{-1} during the last thirty years (Jones, 1992), although yields in Africa remain much lower at around 0.7-1.3 t ha^{-1} (Leng, 1982; Landon, 1991). These yield increases have largely been the result of extensive breeding programmes which have resulted in F1 maize hybrids which provide a uniform crop with predictable characteristics, such as crop duration, resistance to pests and diseases, and harvest index (Loomis and Connor, 1992). The hybrid maize used in this trial was the locally developed Katumani Composite B, a 2 metre tall, 100 day duration, drought resistant variety (Kiepe, 1995).

Response to day length and temperature

Maize is a short-day plant, and requires a minimum uninterrupted dark period to initiate flowering; short-day plants are only found in areas where day length does not exceed approximately 14 h during the period prior to flowering (Jones, 1992). Temperatures below approximately 9-13 °C may prevent growth in maize and can initiate wilting, which may be irreversible after prolonged exposure (Jones, 1992). Research in controlled environments has shown that the growth rate of maize increases with temperature

between 10 and approximately 30 °C and then decreases at supra-optimal temperatures (>35 °C) to reach zero at a temperature of c. 45 °C (Coehlo and Dale, 1980). Cooper and Law (1978) showed that the yield of maize grown at three altitudes in Kenya was greatest at the lowest temperature (highest altitude) due to an increase in the duration of grain filling. Maize is determinate, i.e. there are clearly defined vegetative and reproductive phases caused by the transition of the apical meristem of the stem from producing vegetative organs to producing reproductive structures; a thorough discussion of determinancy, indeterminancy and thermal time can be found in Jones, (1992) and Squire, (1990).

Adaption to drought

Although C4 crops typically have dry matter:water use ratios which are approximately double those of C3 crops and are generally well-adapted to the semi-arid tropics, maize is one of the more drought-sensitive of the C4 crop species (Squire, 1990). The occurrence of drought around flowering has been shown to delay silking and result in the release of pollen in the absence of receptive silks, causing a corresponding reduction in ovule fertilisation and yield (Hall *et al.*, 1982). However, selection under water-stressed conditions has shown that some cultivars can maintain yield under stress (Bolanos and Edmeades, 1988). Under drought conditions, maize exhibits leaf-rolling prior to wilting, which reduces its effective leaf area and shields its stomata from direct contact with the atmosphere in order to minimise water loss (J. Richie, pers. comm.).

Pests and diseases

The principal insect pests of maize are rootworm (e.g. *Diabrotica longicornis*) and stalk borers (e.g. *Pyrausta nubilalis*) which can be controlled through crop rotation (Acland, 1972). Weeds, such as bindweed (*Convolvulus* sp.) or pigweed (*Amaranthus* sp.), pose a more severe problem to maize production than insect pests (Loomis and Connor, 1992). Rippin *et al.* (1994) reported that weed biomass may be reduced by 28-50 % by alley cropping and applications of mulch at high rates (10-12 t ha^{-1}). In practice extremely high rates of mulch application are usually impractical and if trees are successful in suppressing weeds, it is likely that a similar suppression of crop growth will also occur (Ong, 1995).

Cowpea

Cowpea, *Vigna unguiculata* (L.) Walp., is a legume from a diverse genus related to *Phaseolus* and *Dolichos*, and exhibits extensive variation in form, including climbing, erect, semi-erect and spreading varieties (Ng and Maréchal, 1985). Leaf and plant forms of the local Machakos varieties of cowpea are generally similar to those of french or navy beans (*Phaseolus vulgaris*; pers. obs.). Cowpea is a key staple crop for subsistence farmers in many countries, providing more than half of the plant protein in human diets in some areas, with approximately 8 Mha of land under production yielding 2.3 Mt per year world-wide (1981 figures from Rachie, 1985). In the Machakos region cowpea is an important crop, ranking third after maize and beans (Kyolo, pers. com.). Southern and Eastern Africa are the principal centres of diversity for wild relatives and it is in this area that cowpea was probably first domesticated (Baudoin and Maréchal, 1985). It is a dual purpose crop since the leaves are eaten as a form of spinach and the seeds are boiled with maize or fried and eaten with ugali (a stiff maize flour porridge). The seeds are dried in their pods and are easily stored.

Adaptation to drought

Cowpeas have a broad environmental range, extending from short duration cultivars in semi-arid areas to longer duration cultivars in the sub-humid and humid tropics (Summerfield *et al.*, 1985). An experiment involving sixteen genoypes drawn from nine species of grain legume demonstrated a strong positive correlation between leaf area duration and seed yield (Laing *et al.*,1983); thus short duration cowpeas are likely to use less water, but also to produce less yield. However, Rachie (1978) maintained that, when pests and diseases are adequately controlled, yields of 1.6-3.0 t ha^{-1} are achievable within 85 days of sowing. Hall and Patel (1985) suggested that breeding programmes should focus on developing short duration varieties for drought-prone regions. The K-80 cowpea variety grown in the Machakos area is an 80 day duration variety bred at the local Katumani Research Station which forms part of the Kenyan Agricultural Research Institute; 65 day varieties have been developed for more arid environments, such as Northern Senegal (Hall and Patel, 1985). Under water-limited conditions, cowpea avoids drought by exhibiting some or all of the following adaptive features; changes in leaf orientation to a near-vertical posture, reductions in stomatal conductance, or, under more

severe stress, reductions in leaf area (Summerfield *et al.*, 1985).

Waterlogging

Summerfield *et al.* (1985) stated that, even in the semi-arid tropics, high rainfall intensity may result in temporary waterlogging, with consequent adverse effects on cowpea yield. In sites with low inorganic soil nitrogen and little or no application of fertilisers, cowpea is dependent on symbiotic nitrogen fixation. The rhizobium-bearing root nodules are spherical with flattened surface lenticulations which restrict the surface area available for gas exchange and probably render the plants vulnerable to short term exposure to anaerobic conditions (Minchin and Summerfield, 1976). After 16 days of waterlogging under controlled environmental conditions, a 60 % reduction in plant size was observed (Minchin and Summerfield, 1976) and in a separate experiment, yield was reduced by more than 90% following a 4-day period of flooding applied either at three weeks after sowing and or at flowering (Summerfield *et al.*, 1985).

Pests and diseases

Singh and Jackai (1985) stated that insect pests are frequently responsible for complete yield losses in cowpea and listed over 20 major pests prevalent in Africa, including aphids, thrips, pod-borers, leaf worms and weevils; they advocated a range of protective measures including a combination of growing resistant varieties, selective use of insecticide and cultural-control methods. Stigter and Baldy (1995) suggested that intercropping may reduce the spread of pests, citing Lawson and Jackai's (1987) report that thrips infestation of flowers was greatly reduced when cowpea was intercropped with cassava.

Although the wide variety of insect pests is a problem in its own right, these organisms also serve as a vector for diseases; indeed, of the 28 viruses reported for cowpea, 25 were transmitted via insect vectors (Thottappilly and Russell, 1985). In addition to insect pests and viruses, numerous species of fungi, bacteria and nematodes may exert dramatic adverse effects on the growth and yield of cowpea (Emechebe and Shoyinka, 1985).

1.8 LEUCAENA AND GREVILLEA

Leucaena

Leucaena leucocephala (Lam.) de Wit (commonly known as ipil ipil in the Phillipines or su-babul in India) is a leguminous tree of the sub-family Mimosoideae originating in the humid tropics of the Americas (Pound and Martinez-Cairo, 1983). In Hawaii, the natural range of leucaena is within the 650-900 mm rainfall zone. However, outside its natural range leucaena has been reported to grow under mean annual rainfall ranging from 600-3800 mm (ICRAF, Multipurpose Tree Database). Leucaena has been described as the benchmark agroforestry species (Scott, 1991) and is used for fuelwood (e.g. Gunasema, 1989), pole production, and green manure (e.g. Tomar *et al.*, 1992), or as a fodder for a wide range of livestock (e.g. Mitenga, 1991), although the mimosine content of the leaves may render them toxic if consumed in large quantities.

Botanical description

Pound and Martinez-Cairo (1983) provided a detailed botanical description. In brief, leucaena is a shrub or small-to-medium sized tree, with bipinnate leaves on a common rachis 15-20 cm long. The white inflorescences are self-pollinated, producing clusters of up to 60 strap-shaped pods which may reach 20 cm in length and 2 cm in width and contain approximately 20 seeds. Leucaena trees typically have a deep tap root, although there are several varieties ranging from the prostrate Hawaiian type, to the tall single-stemmed Salvadorian type. The latter group includes the high yielding K8 cultivar, which is grown extensively (Brewbaker, 1975) and was used in the Machakos trial discussed in Chapters 2 and 3.

Pests: the leucaena psyllid

Infestation by the leucaena psyllid (*Heteropsylla cubana*) may result in almost complete defoliation (cf. Chapter 2) and is the principal pest of leucaena, having spread from the Caribbean to South and East Asia, Africa and even in New Caledonia (Chazeau *et al.* 1991). The psyllid is particularly successful away from its natural range because it is toxic to many potential predators (Chazeau *et al.* 1991). Attempts have been made to control psyllid populations using a variety of methods. Its natural predator, a ladybird beetle

(*Curinus coeruleus*), was introduced in India with a view to providing biological control, but the predator population did not increase until after the psyllid population had increased after feeding on the first flush of leucaena leaves following the onset of the rains, thereby enabling the psyllid to inflict considerable damage before control could be achieved (Diraviam and Viraktamath, 1990); a similar trial with *C. coeruleus* in Java showed no reduction in psyllid populations or damage to leucaena (Hardi, 1989). Joshi (1991) discussed the use of integrated pest management, incorporating biological control of leucaena psyllids with *C. coeruleus* and some chemical management of pests and diseases in nurseries. In Taiwan, entomopathogenic fungi (*Beauveria bassiana* and *Paecilomyces javanicus*) were isolated from diseased psyllids and cultured in the laboratory; field testing of a conidial suspension of the culture in a heavily psyllid-infested leucaena plantation resulted in reduction of the psyllid population by more than 80 % (Liu *et al.*,1990). Thus, some control of the psyllid is possible, but may require high technology methods which may be prohibitively expensive to small farmers.

Grevillea

Grevillea robusta (commonly known as silver or silky oak) is a proteaceous tree originating in Australia. Its natural range covers 470 km of latitude in Eastern Australia, extending from near the coast to 160 km inland, with precipitation ranging from 720-1710 mm (Harwood, 1992b). Grevillea was introduced to East Africa during the late19th century as a shade tree for tea and coffee and was in use in all coffee plantations around Mt Kilimanjaro during the German Colonial administration prior to 1914 (Haarer, 1956). Indeed, grevillea is so well naturalised in East Africa that it was included in a survey of indigenous tree species in Ethiopian natural forests (Ruden, 1991), and the same mistake has been made in the western Himalaya (Toky and Rhosla, 1984). An ICRAF survey in Kenya found that grevillea was the most popular tree with farmers and that nurseries could not keep up with demand (Ongugo, 1992). The principal uses of grevillea reported in a survey of the Meru and Embu districts of Kenya were timber, fuelwood and poles/rafters, with windbreaks, fodder and soil erosion control being considered as secondary or tertiary uses (Spiers and Stewart, 1992). Harwood (1989) has compiled a useful annotated bibliography of grevillea, while Harwood (1992a) edited the proceedings of an international workshop on the use of grevillea in agroforestry and

forestry.

Botanical description

Grevillea may attain a height of 27 m, with a diameter at breast height of 100 cm, usually reaching 9 metres within the first 6 years (Harwood, 1992b). It has large leaves, which are alternate, pinnately compound and exhibit xeromorphic features (Thimma Raju, 1992). Its large yellow flowers, with a large nectar store, are primarily pollinated by birds, and the seeds are winged.

Pests and diseases

Grevillea has few pests in its natural environment and few adverse effects of diseases have been reported (Harwood, 1992b). However, outside its natural range young grevillea saplings are prone to termite damage and insecticide applications may be necessary (Raunio, 1975).

Suitability of grevillea and leucaena for agroforestry

Leucaena has been the subject of numerous agroforestry studies (Corlett, 1989) as it is a fast-growing multipurpose tree, although much of its initial popularity lay in its nitrogen-fixing ability. Ong (1995) pointed out that there is little evidence of direct nitrogen transfer between leguminous trees and non-leguminous intercrops, and that most reports of yield advantages may be attributed to factors other than nitrogen transfer (e.g. increased availability of soil nitrogen resulting from the planting arrangement adopted).

Huxley (1983) suggested that the different rooting depths of trees and crops should have positive benefits by increasing resource capture and minimising competition. However, Jonsson *et al.* (1988) showed substantial overlap in the distribution of the fine roots of maize with those of several tree species; this effect was particularly prevalent in leucaena (Fig. 1.11). Laycock and Wood (1963) studied the effect of shade trees on tea production and found that yields were significantly less under *Gliricidia maculata* and *Albizzia gummifera* than in either the grevillea or control treatments. Although they initially attributed this difference to the density of shade, on examination of the roots they showed that *G. maculata* and *A. gummifera* had extensive lateral root systems whereas

grevillea possessed few superficial lateral roots and the bulk of the roots were concentrated under the bole of the tree. Figure 1.12 shows the vertical distribution of the fine roots of four agroforestry tree species intercropped with sugar cane. Grevillea clearly had the lowest biomass of fine roots in the upper 60 cm of the soil profile, as was reflected by the yield of sugar cane which was negatively correlated with the fine root biomass of the intercropped trees (cane yield was greatest under grevillea and least under casuarina; Mwihomeke, 1992). Grevillea shade has been reported to have both positive (Visser, 1960) and negative effects (Otheino, 1983) on the yield of tea. Whichever tree species is used in agroforestry systems, the existence of any spatial and temporal complementarity will depend on the crop species with which it is combined, the management regime imposed and the local climatic and soil conditions. Snaydon and Harris (1981) suggested that below-ground interactions maybe more important than above-ground interactions, and that the success or failure of agroforestry system may be largely controlled by the rooting habit of the tree species.

1.9 AIMS AND OBJECTIVES

The main objective of the work described here was to study the capture and utilisation of light and water in tree/crop mixtures and to evaluate factors which determine complementarity and competition. The more specific aims were to:

1) establish the extent and nature of above and below-ground competition in leucaena/maize agroforestry systems;
2) quantify the principal components of the water budget in grevillea/cowpea agroforestry systems on sloping land;
3) establish the extent and nature of competition and complementarity in grevillea/cowpea agroforestry systems on sloping land.

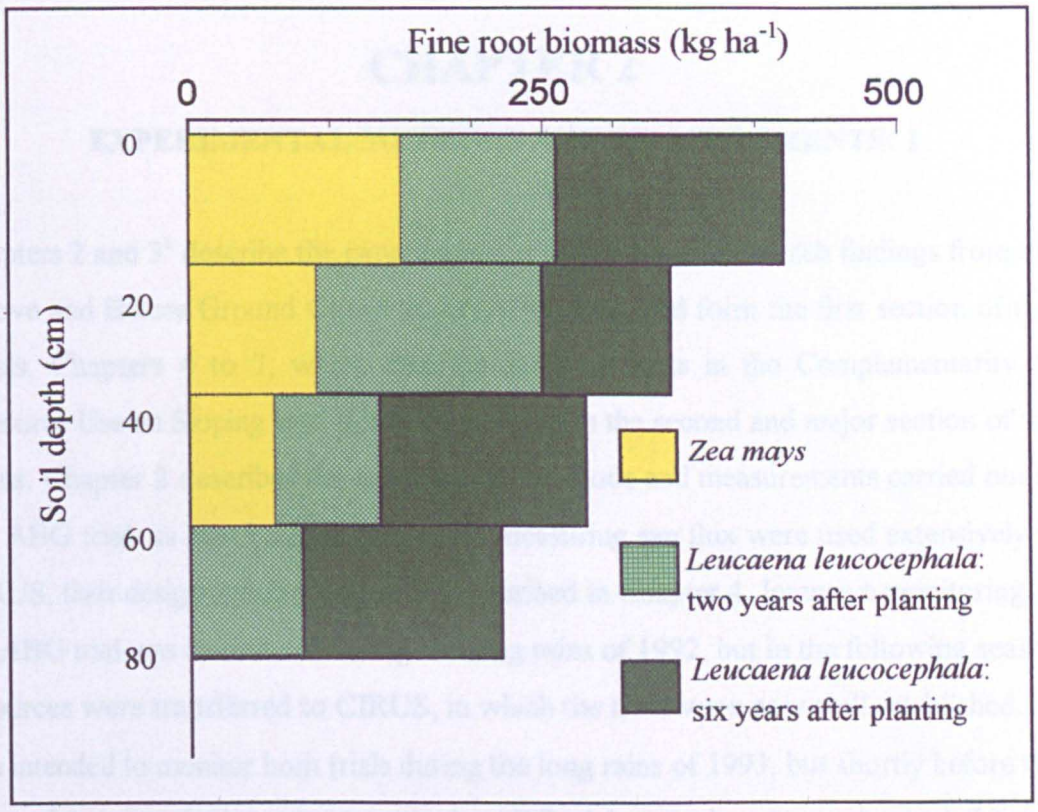

Figure 1.11 Vertical distribution of fine root biomass of maize and *Leucaena leucocephala* in Morogoro, Tanzania (after Jonsonn *et al.*, 1988).

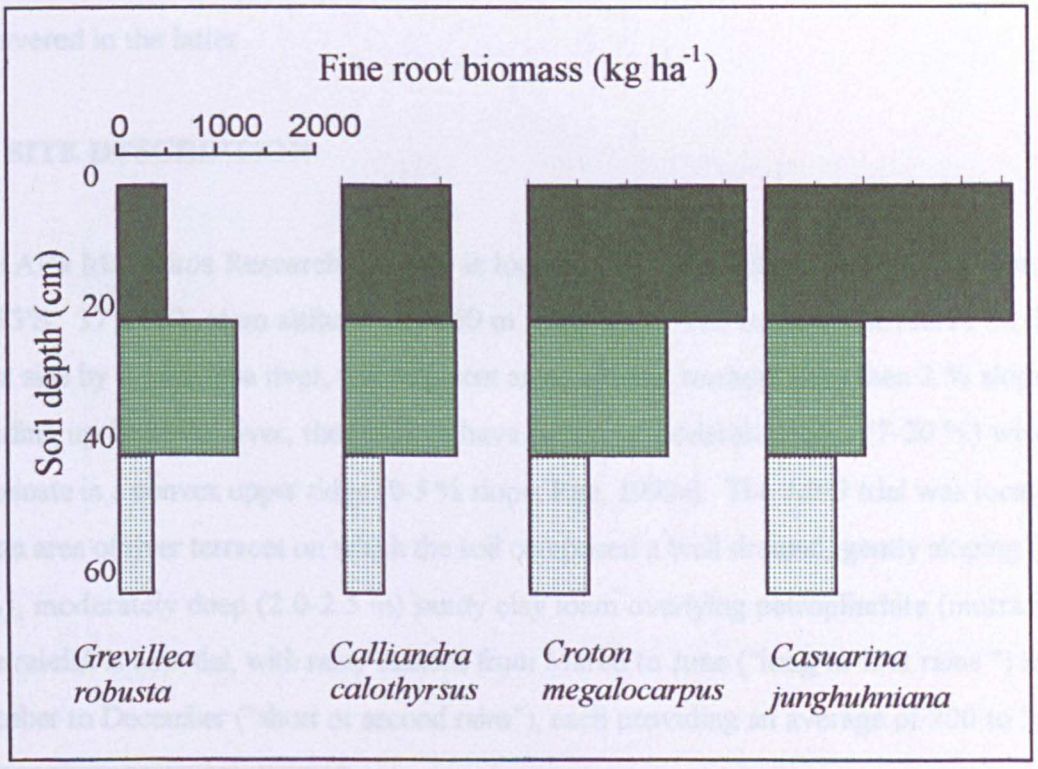

Figure 1.12 Vertical distribution of fine root biomass of four tree species intercropped with sugar cane in Lushoto, Tanzania (redrawn from Mwihomeke, 1992).

CHAPTER 2

EXPERIMENTAL METHODS AND MEASUREMENTS: 1

Chapters 2 and 3[1] describe the experimental programme and research findings from the Above and Below Ground Competition (ABG) trial, and form the first section of this thesis. Chapters 4 to 7, which describe similar studies in the Complementarity In Resource Use on Sloping land (CIRUS) trial, form the second and major section of the thesis. Chapter 2 describes the experimental methods and measurements carried out in the ABG trial: as heat balance gauges for measuring sap flux were used extensively in CIRUS, their design and application are described in Chapter 4. Intensive monitoring of the ABG trial was carried out during the long rains of 1992, but in the following season resources were transferred to CIRUS, in which the trees were now well established. It was intended to monitor both trials during the long rains of 1993, but shortly before the onset of the rains the leucaena trees in the ABG trial were almost completely defoliated by psyllid (*Heteropsylla cubana*) infestation: in both subsequent seasons, the grevillea trial was studied in preference to the leucaena trial as the trees had only partially recovered in the latter.

2.1 SITE DESCRIPTION

ICRAF's Machakos Research Station is located 70 km southeast of Nairobi, Kenya (1°33'S, 37°14'E), at an altitude of 1660 m (Fig. 2.1). The station is bordered on the west side by the Maruba river, with adjacent areas of river terraces (less than 2 % slope). Leading up from the river, the terraces have gentle to moderate slopes (7-20 %) which terminate in a convex upper ridge (0-5 % slope; Rao, 1992a). The ABG trial was located on an area of river terraces on which the soil comprised a well drained, gently sloping (2-4%), moderately deep (2.0-2.5 m) sandy clay loam overlying petroplinthite (murram). The rainfall is bimodal, with rainy seasons from March to June ("long or first rains ") and October to December ("short or second rains"), each providing an average of 300 to 350

[1] Chapters 2 and 3 are drawn from Howard *et. al.*, (1995). Chapter 3 is largely unchanged; however additional information on materials and methods is provided in Chapter 2.

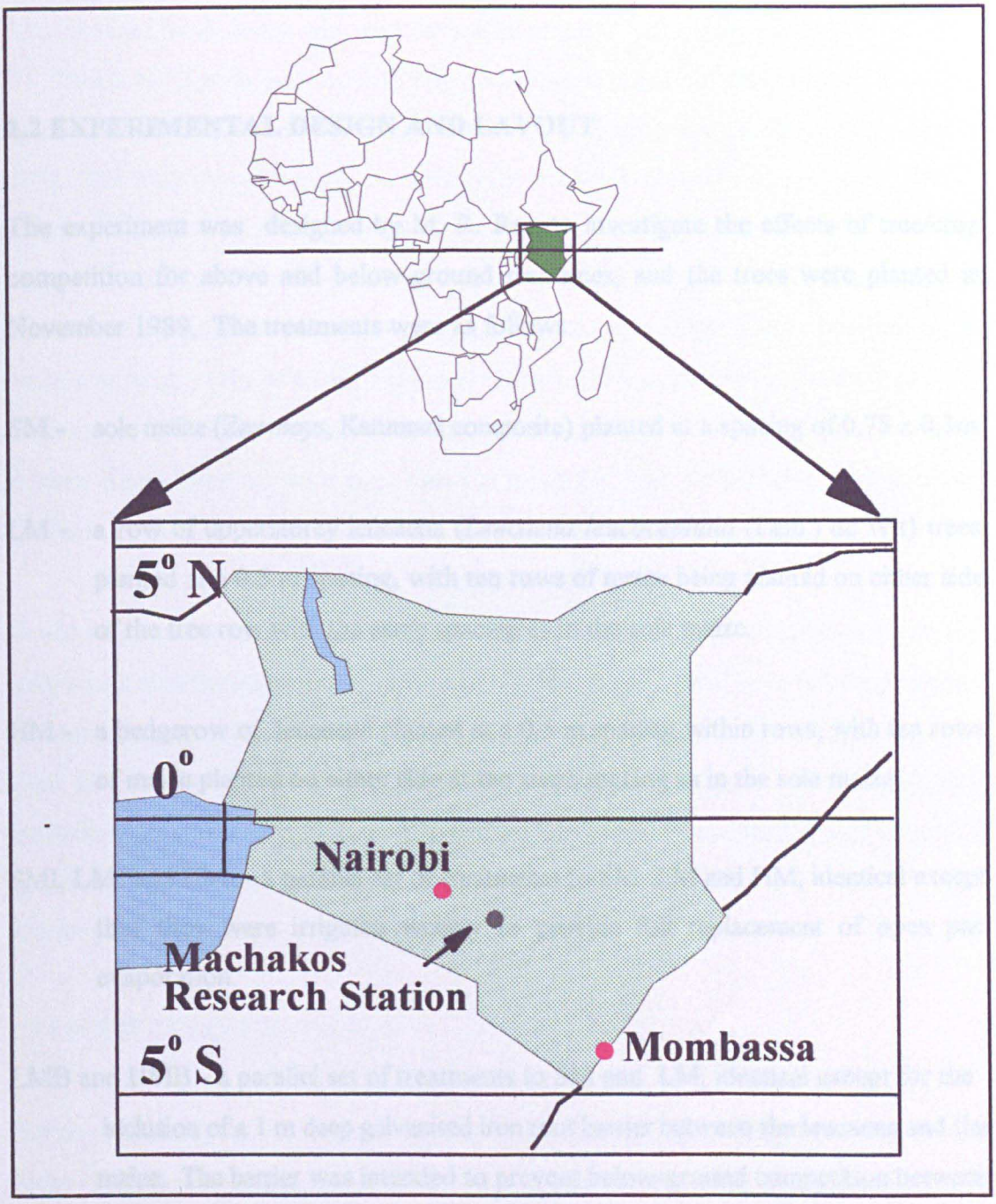

Figure 2.1 The location of the International Centre for Research in Agroforestry (ICRAF) Machakos Research Station, Kenya.

mm, with a long-term annual average of 760 mm. In the long rains of 1992, the total rainfall was 237 mm, with more than 95% falling during the first 26 days after sowing (DAS).

2.2 EXPERIMENTAL DESIGN AND LAYOUT

The experiment was designed by M. R. Rao to investigate the effects of tree/crop competition for above and below-ground resources, and the trees were planted in November 1989. The treatments were as follows:

SM - sole maize (*Zea mays*, Katumani composite) planted at a spacing of 0.75 x 0.3m.

LM - a row of upperstorey leucaena (*Leucaena leucocephala* (Lam.) de Wit) trees planted at a 0.5 m spacing, with ten rows of maize being planted on either side of the tree row with the same spacing as in the sole maize.

HM - a hedgerow of leucaena planted at a 0.5 m spacing within rows, with ten rows of maize planted on either side at the same spacing as in the sole maize.

SMI, LMI and HMI - a parallel set of treatments to SM, LM and HM, identical except that they were irrigated weekly to provide full replacement of open pan evaporation.

LMB and HMB - a parallel set of treatments to SM and LM, identical except for the inclusion of a 1 m deep galvanised iron root barrier between the leucaena and the maize. The barrier was intended to prevent below-ground competition between trees and crops.

SH - sole hedgerow leucaena.

TH - identical to HM except that the hedgerow leucaena was planted in a 40 cm deep

by 40 cm wide trench. The trench was kept open by galvanised iron sheets supporting the walls.

A randomised block design was used and each treatment was replicated three times (Fig. 2.2, Plate 2.1). The plots were 15.75 by 10 m in area and were aligned along the slope by contour-planting the tree or hedgerow (or central crop row in the case of SM and SMI). The tree rows or hedgerows were kept at least 4 m away from adjacent plots to reduce the risk of interference between plots. The areas between the plots and a 3 m margin around the outer plots were cropped to minimise edge-effects. Leucaena was established by planting three month old, container-grown seedlings. The hedgerow treatments were pruned at a height of 0.5 m at the beginning, middle and end of the rainy seasons. In the first year after planting, the upperstorey trees were side-pruned to produce single stems and were more than 4 m tall at the onset of the 1992 long rains. No fertilisers were applied and no residues were incorporated into the soil.

Monitoring of resource partitioning was impractical in the TH treatment due to the sunken nature of the hedge, and in any case, this treatment was of little practical interest because of its unsuitability for on-farm application. The barriers proved ineffective in the LMB and HMB treatments, as the tree roots grew beneath them and then extended upwards into the surface horizons. Due to these factors and limitations of equipment and labour, the treatments monitored in detail were SM, LM, HM and their irrigated counterparts, SMI, LMI, and HMI.

2.3 LIGHT INTERCEPTION

Photosynthetically active radiation (PAR) was measured using a Sunfleck Ceptometer (Delta-T Devices, UK) at 7 -10 d intervals. These measurement intervals (as for the neutron probe) were chosen to provide sufficiently detailed data to establish temporal trends without causing excessive disturbance to the plots. Measurements were made at mid-day above and below the trees and crop in transects spanning all rows of maize on both sides of the tree rows for all replicates (Fig. 2.3): ten maize rows were measured in each of the SM and SMI plots.

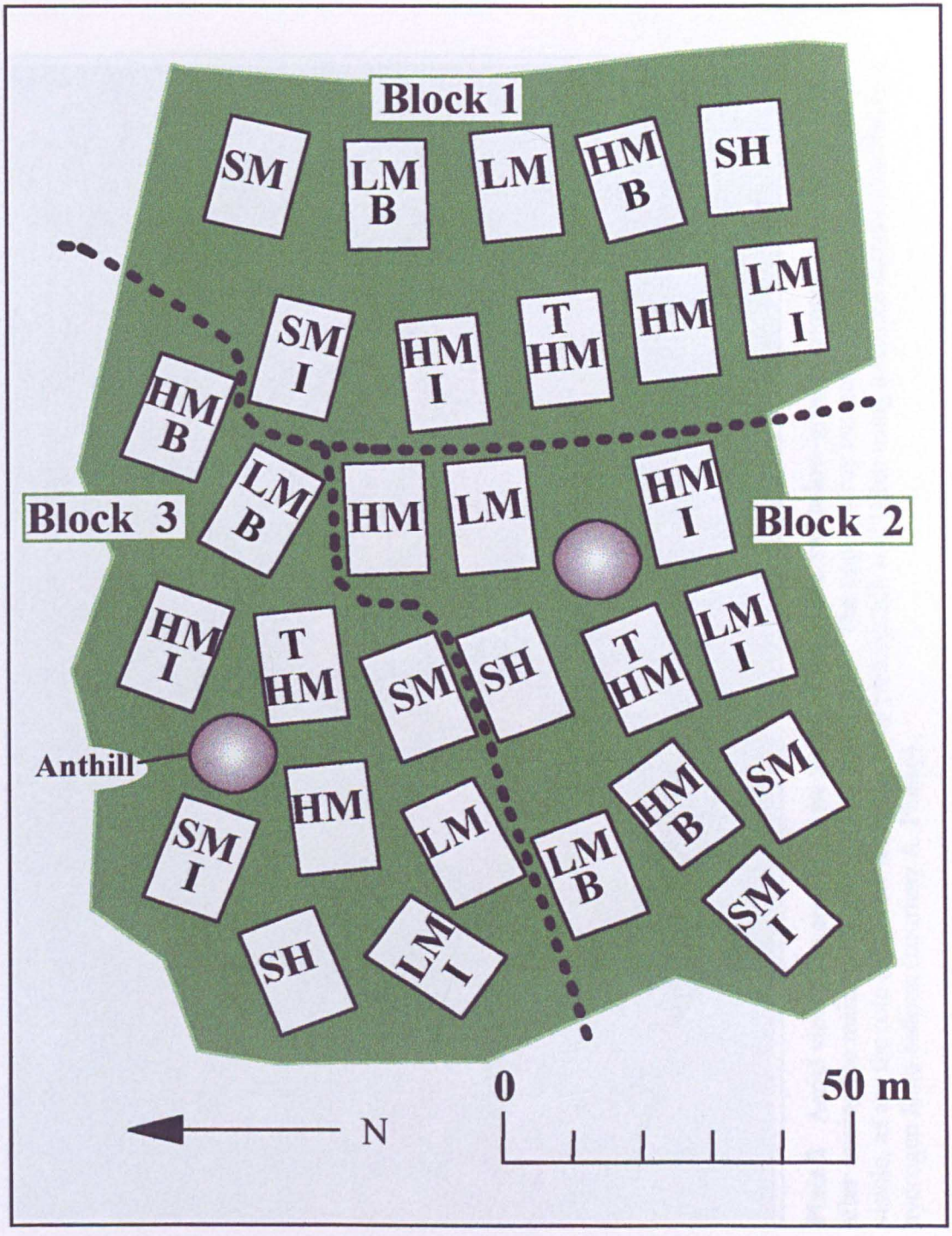

Figure 2.2 Layout of the leucaena/maize competition for Above and Below Ground resources trial (ABG). The cropped area between the plots is shaded.

Plate 2 Aerial view of an area (c. 75 by 50 m) of the above and below-ground competition trial, 30 days after sowing the maize during the 1992/3 short rains. The upperstorey leucaena tree canopies are clearly visible, as are the sole hedgerow leucaena. The photograph was taken using a remote camera attached to a hydrogen filled balloon (courtesy A. Pinney).

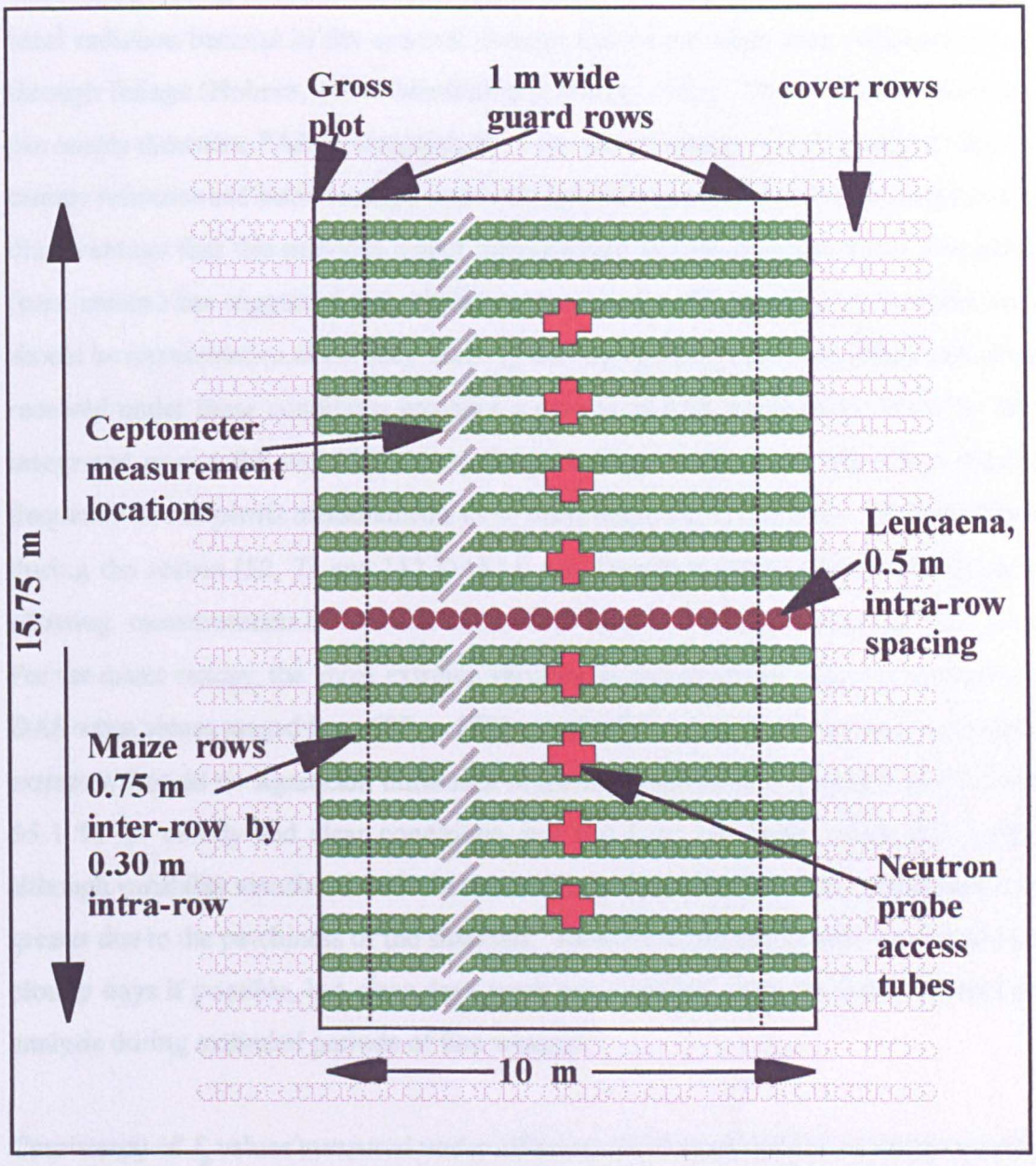

Figure 2.3 Plot layout and measurement points in the HM and LM plots. LMI and HMI plots were identical except for the absence of neutron probe access tubes.

When measuring light interception in mixed communities, especially where the canopies of the component species are distinct, it is preferable to measure PAR fluxes rather than total radiation because of the spectral changes that occur when solar radiation passes through foliage (Holmes, 1981; Marshall and Willey, 1983). The sunfleck ceptometer can readily determine PAR interception (f_p) from paired measurements (using an above-canopy reference and below-canopy measurements of transmitted radiation), but has the disadvantage that this provides a spot measurement in both time and space. Campbell (pers. comm.) has suggested that midday measurements of f_p made on an overcast days should be representative of the daily mean f_p; the largely non-directional diffuse radiation received under these conditions provides a pattern of light distribution similar to that integrated over a full day. However, the prevailing conditions in Machakos district frequently do not permit measurements to be made only on overcast days. At three times during the season (52, 73 and 112 DAS) f_p was therefore measured on variable days, allowing measurements to be made under both clear and cloudy conditions (Fig. 2.4). For the maize canopy, the most extreme variation in incident PAR was recorded at 112 DAS when values ranged from 608 to 2772 μmol $m^{-2}s^{-1}$; measurements made near these extremes showed no significant difference in the mean values of f_p (mean f_p of 63.8 and 65.1 % for cloudy and clear conditions, $p > 0.4$ from two-tailed t-test, d.f. = 68), although variability associated with the measurements made under clear conditions was greater due to the patchiness of the shadows. As a result, measurements were made on cloudy days if possible, but clear days were not excluded from the measurements or analysis during extended periods of fine weather.

Consistency of f_p values measured under different cloud conditions is a canopy-specific property and clearly did not apply to the upperstorey tree rows, which exhibited mean f_p values under clear skies that were 10-20% higher than those recorded under overcast conditions; f_p was overestimated under and adjacent to the tree row and slightly underestimated farther away due to the smaller penumbral area. To enable tree f_p to be derived from the measurements made on clear days as well as on cloudy days, the ratios of measurements made under cloudy conditions to those made under clear conditions were calculated to provide row-wise correction factors (simple multipliers) for all

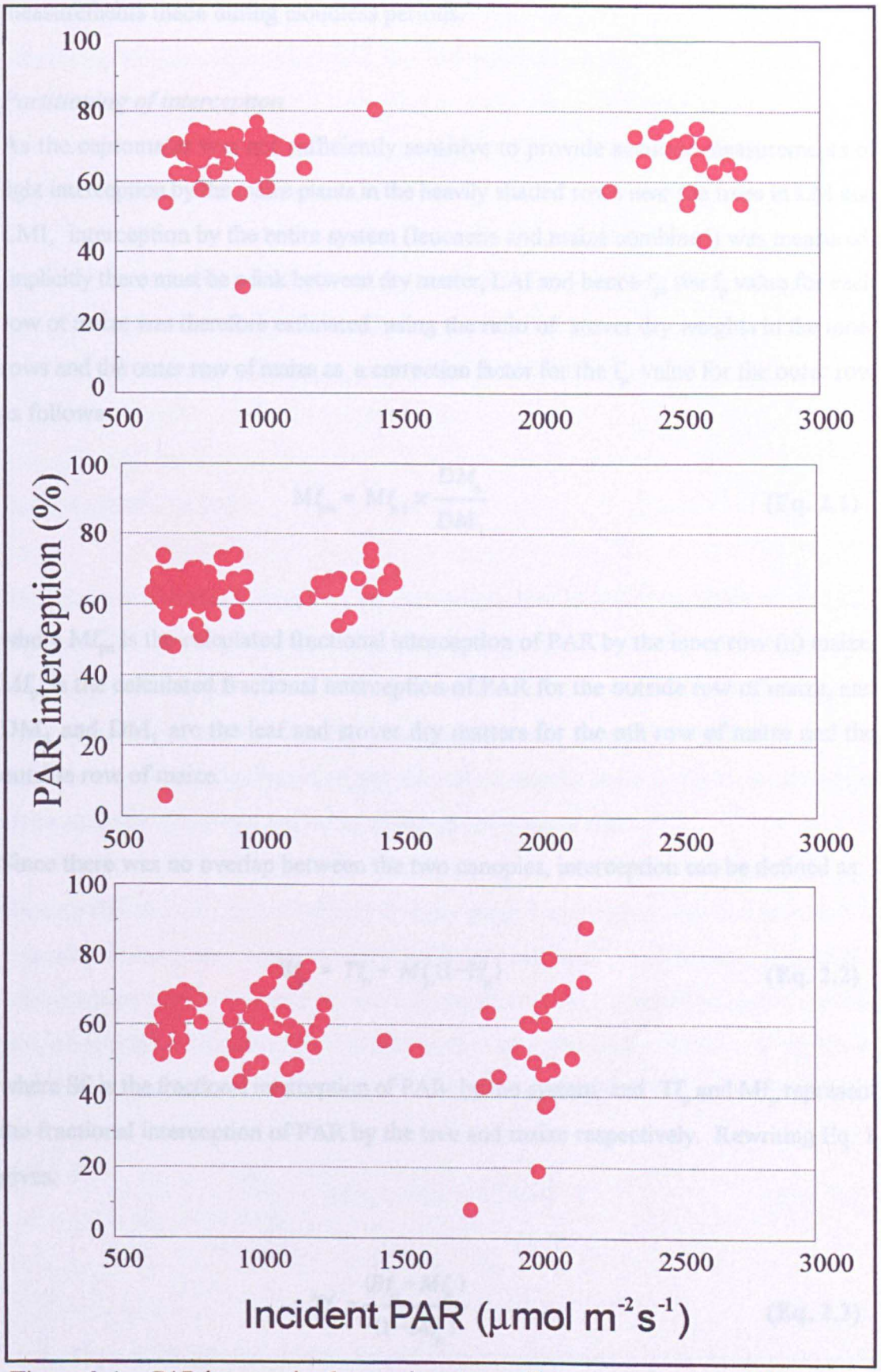

Figure 2.4 PAR interception by a maize canopy (fp) measured under diffuse and direct sunlight at three times during the season (52, 73 and 112 DAS).

measurements made during cloudless periods.

Partitioning of interception

As the ceptometer was not sufficiently sensitive to provide accurate measurements of light interception by the maize plants in the heavily shaded rows near the trees in LM and LMI, interception by the entire system (leucaena and maize combined) was measured. Implicitly there must be a link between dry matter, LAI and hence f_p; the f_p value for each row of maize was therefore estimated using the ratio of stover dry weights in the inner rows and the outer row of maize as a correction factor for the f_p value for the outer row as follows:

$$Mf_{pn} = Mf_{p1} \times \frac{DM_n}{DM_1} \qquad \textbf{(Eq. 2.1)}$$

where Mf_{pn} is the calculated fractional interception of PAR by the inner row (n) maize, Mf_{p1} is the calculated fractional interception of PAR for the outside row of maize, and DM_n and DM_1 are the leaf and stover dry matters for the nth row of maize and the outside row of maize.

Since there was no overlap between the two canopies, interception can be defined as:

$$Sf_p = Tf_p + Mf_p(1-Tf_p) \qquad \textbf{(Eq. 2.2)}$$

where Sf_p is the fractional interception of PAR by the system, and Tf_p and Mf_p represent the fractional interception of PAR by the tree and maize respectively. Rewriting Eq. 1 gives:

$$Tf_p = \frac{(Sf_p - Mf_p)}{(1 - Mf_p)} \qquad \textbf{(Eq. 2.3)}$$

Since Sf_p and Mf_p could be previously calculated, Tf_p may be determined and the actual

fraction of PAR intercepted by the maize ($(1 - Tf_p)Mf_p$) derived. Although the relationship between light interception and leaf and stalk weight is likely to be non-linear over a large range of values, with plants of a similar size it should be close to linear and provide a reasonable estimate of Mf_p, given that Tf_p plays a major role in determining light interception by the inner rows of maize.

Intercepted PAR was calculated using the values of Tf_p and Mf_p, with a simple linear interpolation for intervening dates; incident photon flux density was assumed to be 0.5 of total incident solar radiation (Cannell, 1989).

2.4 TRANSPIRATION

Sap flux was measured using heat balance gauges (as described by Ishida *et al.*, 1992) and modified by A A H Khan, ICRAF, see Chapter 4 for full description) linked to dataloggers (Campbell CR21X). Gauges were attached to three trees in both the HM and LM treatments and to 3-6 maize plants in SM (commencing five weeks after sowing) for two to three week periods at regular intervals during the season. Representative trees were selected on the basis of collar diameter and canopy size.

Due to the limited number of heat balance gauges available at any one time, it was necessary to interpolate values for maize in SM and leucaena in LM between consecutive measurement periods. Multiple regression analysis of daily transpiration against incident and intercepted PAR, days after emergence (DAE) and their quadratics was performed and the equations providing the best fit were used for interpolation as follows:

$$\frac{Et_m}{4.44} = aDf_{pt} + bDAE - cDAE^2 \qquad \textbf{(Eq. 2.4)}$$

where Et_m is the daily transpiration by maize (g m^{-2}, adjusted for population), Df_{pt} is the daily total intercepted PAR (MJ m^{-2}), a is 41.6, b is 4.81 and c is 0.0623 (s.e. 5.0, 2.1,

and 0.023 respectively; v.r. 127.6, with 35 d.f.; 60.7 % of the variation accounted for). Tree transpiration was calculated using the relation:

$$Et_l \times 7.88 = aDt_p + bDAE - cDAE^2 \qquad \textbf{(Eq. 2.4)}$$

where Et_l is the daily transpiration by leucaena (g m^{-2}, adjusted for population), Dt_p is the daily total incident PAR (MJ m^{-2}), a is 514.6, b is 128.2 and c is 0.752 (s.e 45.6, 15.1, and 0.11 respectively; v.r. 1250.5, with 39 d.f.; 67.8% of the variation accounted for). Estimates of seasonal transpiration were obtained using the above equations and the appropriate values for daily total intercepted PAR for the maize and daily total incident PAR for the leucaena. Intercropped maize was assumed to have the same transpired water:dry matter ratio (e_w) as sole maize and seasonal transpiration was estimated using this value. The estimation of transpiration by the hedgerow leucaena (in HM) was complicated by the mid-season pruning of the leucaena and a continually changing degree of shading by the associated maize crop (the maize crop over-topped the hedge at 30-40 DAS). However, sufficient transpiration measurements were made during the season to allow some comparison with the upperstorey leucaena.

2.5 SOIL WATER

Investigation of below-ground competition for soil moisture was a key component of the ABG trial and soil moisture profiles were measured at weekly intervals using a Wallingford neutron soil moisture gauge (Bell, 1987). Eight aluminium neutron probe access tubes were installed to a depth of 2 m at 1.5 m intervals along a transect crossing the tree rows in each of the LM and HM plots (Fig. 2.3): eight tubes were also placed in the SM plots. Measurements were made at 15 cm intervals to a depth of 180 cm.

Field calibration

Various methods may be used to obtain calibrations curves relating probe count to volumetric soil moisture for specific sites; for example Bell (1987) suggested theoretical

calculations, laboratory-based drum calibrations and field calibrations as alternatives. Theoretical calculations may be based on either highly detailed analysis of soil chemistry or analysis of the back-scatter of macro cross-sections under an atomic pile. These analytical approaches are expensive and dependent on the reliability of both the field sampling and the laboratory analysis. Laboratory-based drum-calibrations require the repacking of soil into a drum in a way that closely resembles its field condition. The moderate clay content of the soil from the trial site would not permit it to be repacked in such away. Because of these various considerations, an on-site field calibration was performed at the end of the 1992 long dry season when the soil profiles were at their driest.

Field calibration can be difficult in highly heterogeneous soils containing several physically contrasting horizons. However, the soil at the ABG site is quite homogeneous, with no visible change in horizon until the petroplinthite layer is reached 2.0-2.5 m; the site is almost free of gravel and small stones.

For a complete field calibration, it is preferable to obtain soil moisture values and probe readings over the full range of values likely to be experienced. Paired tubes were selected in each replicate: one was used for calibration of drier soils and the other for wetted soil. In order to calibrate the probe under wet soil conditions, the soil was artificially saturated (Fig. 2.5) and left for 18 - 36 h to drain to near field capacity, rather than risk the disturbance of crops during the rainy season. For both non-wetted and wetted soils, samples were taken at a distance of 40-50 cm from the tubes, immediately after completing a set of probe readings (Fig. 2.6). In the drier soil, a 10 cm diameter steel corer was driven into the soil and 5-6 cm long cores were taken; the centre of each core was coincident with a probe reading depth. A steel corer was employed in the dry soil because of its extreme hardness; this was the only method that could successfully penetrate to a depth of 2 m. The wetted soil was considerably softer and more plastic than the dry soil and care had to be taken to avoid compaction during sampling. Consequently an auger was used to remove soil to 5-10 mm above the required sampling depth, at which point a pF ring (a steel ring with a 5 cm diameter and 5 cm depth, used to extract undisturbed soil samples for laboratory analysis of moisture retention at

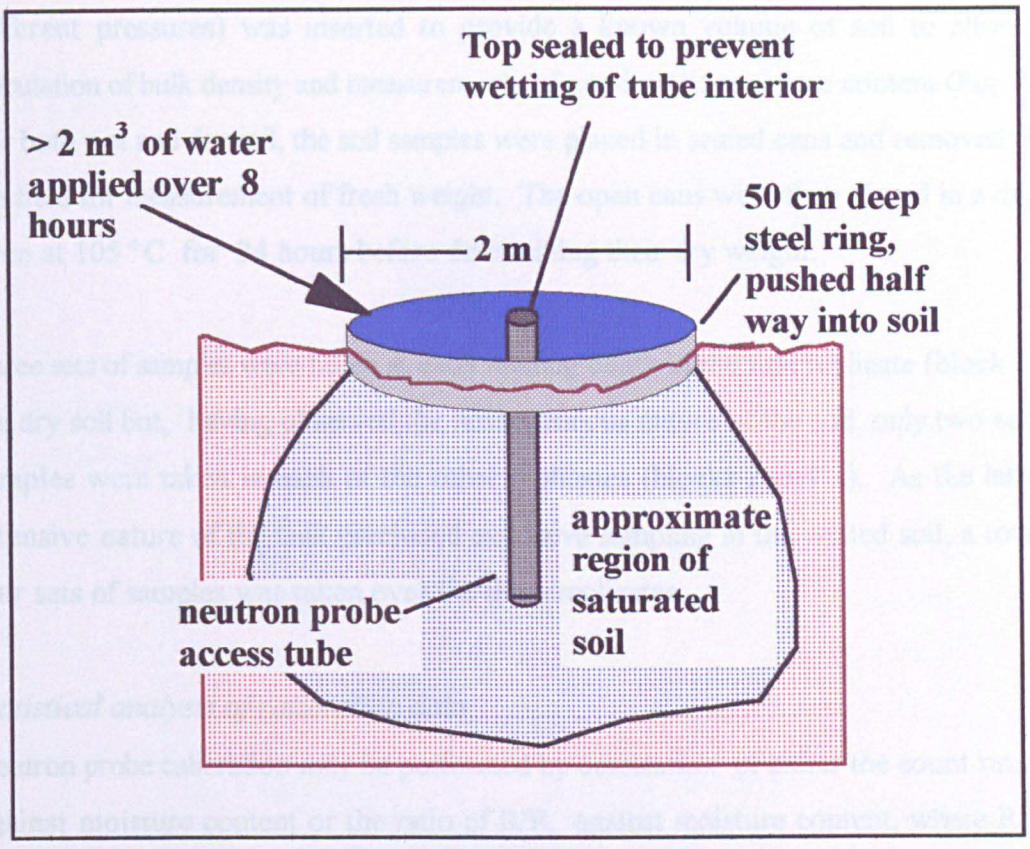

Figure 2.5 Soil wetting procedure for calibration of the neutron probe

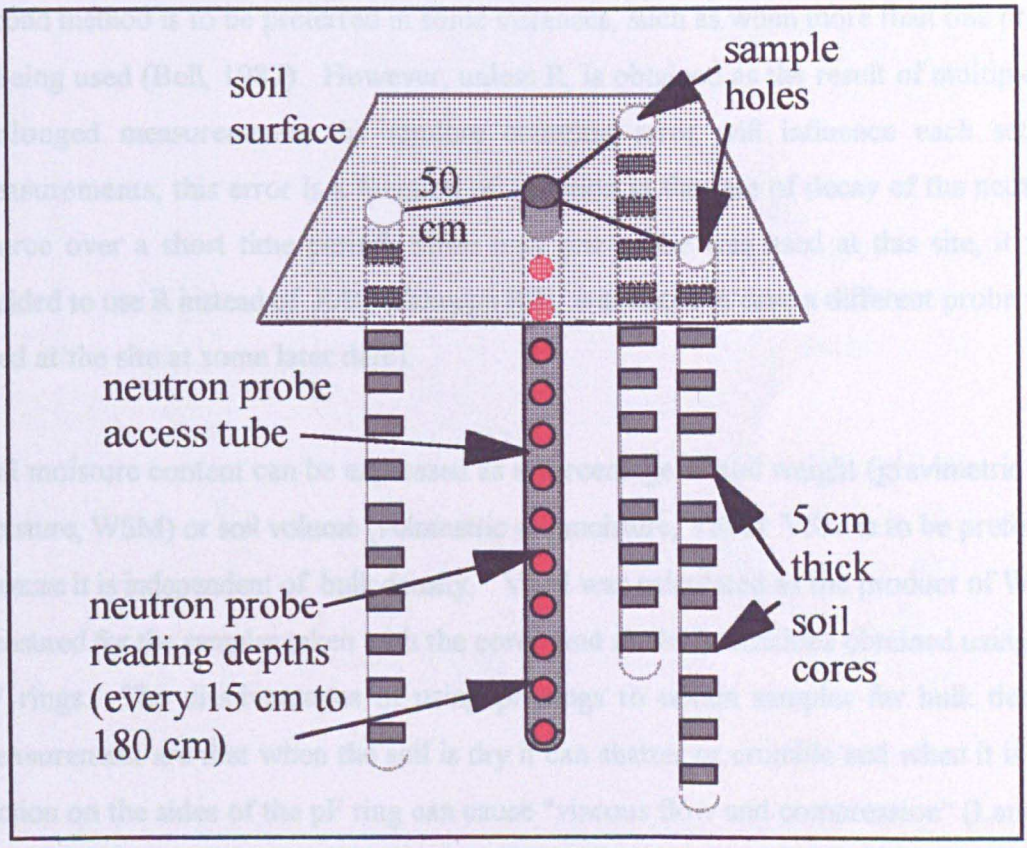

Figure 2.6 Soil sampling positions for neutron probe calibration.

different pressures) was inserted to provide a known volume of soil to allow the calculation of bulk density and measurements of gravimetric moisture content (Fig. 2.7). For both wet and dry soil, the soil samples were placed in sealed cans and removed from the field for measurement of fresh weight. The open cans were then placed in a drying oven at 105 °C for 24 hours before determining their dry weight.

Three sets of samples were taken at each reading depth in the first replicate (block 1) of the dry soil but, having observed the homogeneous nature of the soil, only two sets of samples were taken in each of the other replicates (blocks 2 and 3). As the labour-intensive nature of the task precluded extensive sampling in the wetted soil, a total of four sets of samples was taken over the three replicates.

Statistical analysis of calibration data

Neutron probe calibration may be performed by correlation of either the count rate (R) against moisture content or the ratio of R/R_s against moisture content, where R_s is a standard count usually taken in a drum of water before each set of measurements. The second method is to be preferred in some instances, such as when more than one probe is being used (Bell, 1987). However, unless R_s is obtained as the result of multiple or prolonged measurements, the random counting error will influence each set of measurements; this error is a function of variation in the rate of decay of the neutron source over a short time period. Since only one probe was used at this site, it was decided to use R instead of R/R_s (although R/R_s was noted in case a different probe was used at the site at some later date).

Soil moisture content can be expressed as a percentage of soil weight (gravimetric soil moisture, WSM) or soil volume (volumetric soil moisture, VSM): VSM is to be preferred because it is independent of bulk density. VSM was calculated as the product of WSM measured for the samples taken with the corer and the bulk densities obtained using the pF rings. The disadvantages of using pF rings to obtain samples for bulk density measurement are that when the soil is dry it can shatter or crumble and when it is wet friction on the sides of the pF ring can cause "viscous flow and compression" (Landon, 1991). In Figure 2.8, the wet samples consistently show higher VSM values at specific

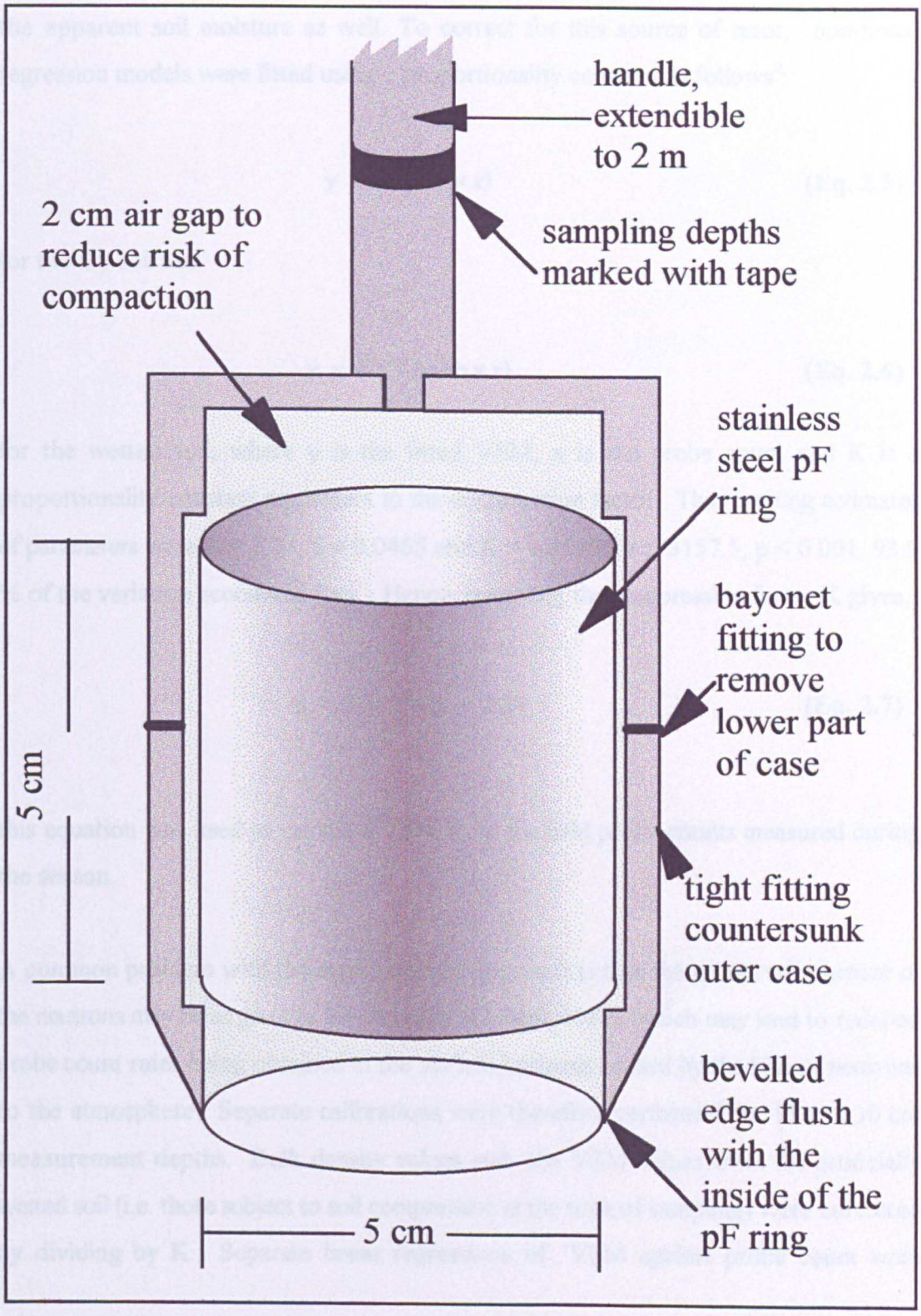

Figure 2.7 pF ring and outer case, for sampling a known volume of soil.

count rates than the dry samples. This is indicative of compression of the sample within the pF ring. Such compression will increase not only the measured bulk density, but also the apparent soil moisture as well. To correct for this source of error, non-linear regression models were fitted using a proportionality constant as follows[2]:

$$y = K(a + b \times x) \qquad \textbf{(Eq. 2.5)}$$

for the dry soil and

$$y = K \times K(a + b \times x) \qquad \textbf{(Eq. 2.6)}$$

for the wetted soil, where y is the fitted VSM, x is the probe count and K is a proportionality constant equivalent to the compression factor. The resulting estimates of parameters were, a = 2.34, b = 0.0465 and K = 1.3595 (v.r. 3157.5, $p < 0.001$, 93.9 % of the variation accounted for). Hence, removing the compression factor K gives,

$$y = 0.0465 \times x + 2.34 \qquad \textbf{(Eq. 2.7)}$$

this equation was used to calculate VSM from the field probe counts measured during the season.

A common problem with the neutron probe approach is that the sphere of influence of the neutrons may be as great as 30 cm in dry soil (Bell, 1987), which may lead to reduced probe count rates being obtained in the surface horizons caused by the loss of neutrons to the atmosphere. Separate calibrations were therefore performed for 15 and 30 cm measurement depths. Bulk density values and the VSM values from the artificially wetted soil (i.e. those subject to soil compression at the time of sampling) were corrected by dividing by K. Separate linear regressions of VSM against probe count were

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[2] See Genstat 5.2 Reference Manual (1988) for an explanation of multiple regression analysis with proportionality constants.

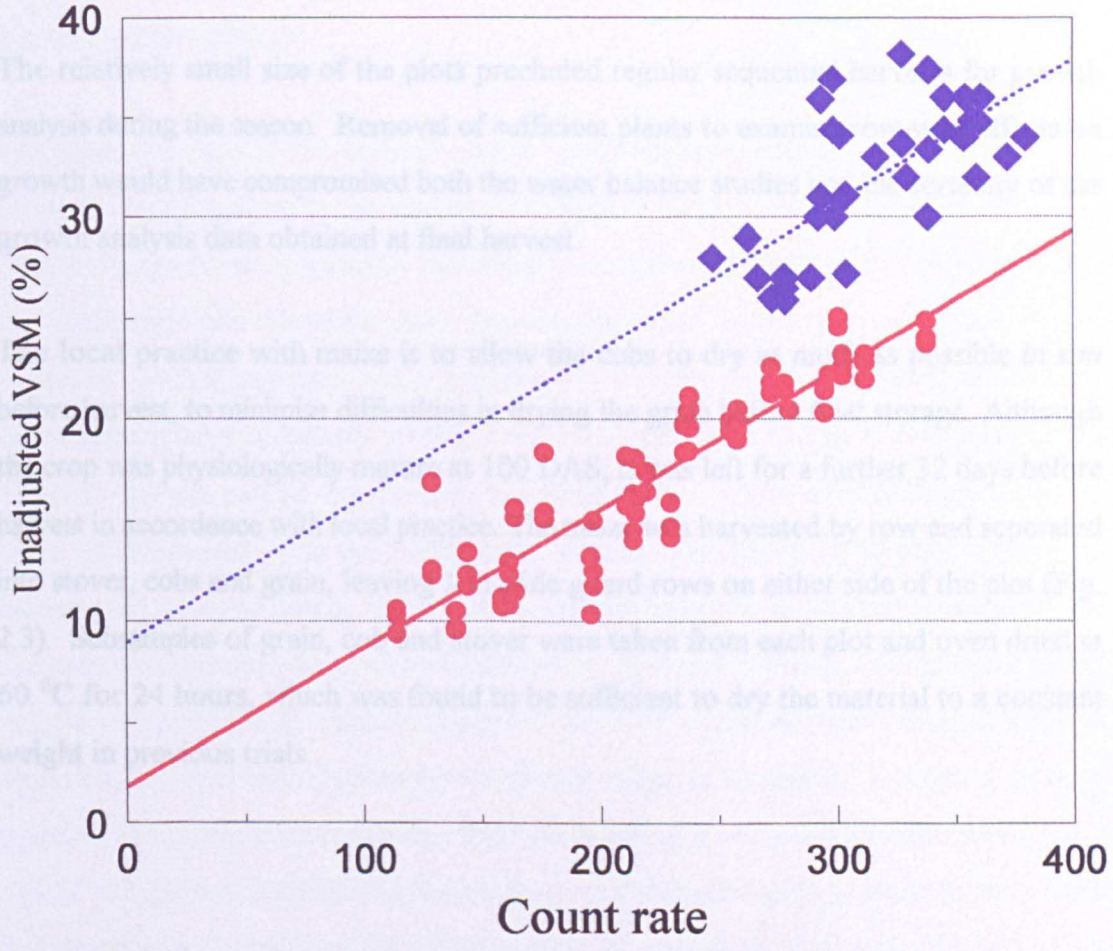


Figure 2.8 Correlation between unadjusted volumetric soil moisture (VSM) and neutron probe count rate. Values are shown for core samples taken from dry soil (●, $y = 0.069x + 1.84$, $r^2 = 0.83$, $n = 80$) or from pF ring samples taken from artificially wetted soil (◆, $y = 0.072x + 8.95$, $r^2 = 0.51$, $n = 40$). Bulk density values for the wetted samples were used to calculate the volumetric soil moisture content.

performed for measurements made at 15 and 30 cm, thereby allowing VSM to be calculated from the probe count rates at all measurement depths.

2.6 MAIZE HARVEST

The relatively small size of the plots precluded regular sequential harvests for growth analysis during the season. Removal of sufficient plants to examine row-wise effects on growth would have compromised both the water balance studies and the certainty of the growth analysis data obtained at final harvest.

The local practice with maize is to allow the cobs to dry as much as possible *in situ* before harvest, to minimise difficulties in drying the grain before final storage. Although the crop was physiologically mature at 100 DAS, it was left for a further 32 days before harvest in accordance with local practice. The maize was harvested by row and separated into stover, cobs and grain, leaving 1 m wide guard rows on either side of the plot (Fig. 2.3). Subsamples of grain, cob and stover were taken from each plot and oven dried at 60 ^{0}C for 24 hours, which was found to be sufficient to dry the material to a constant weight in previous trials.

CHAPTER 3

ABOVE AND BELOW GROUND COMPETITION IN LEUCAENA/MAIZE AGROFORESTRY SYSTEMS[1]

3.1 INTRODUCTION

The yield advantage of conventional annual intercropping systems has been explained in terms of improvements in the capture or utilisation of growth resources (Willey *et al.*, 1986). In agroforestry systems, the tree component is perennial, effectively increasing the duration of the otherwise short growing season(s) to span the entire year. Thus, resource capture by agroforestry systems may be expected to be greater than in sole crops, although not necessarily greater than in the optimum sole tree system (Ong *et al.*, 1991b). The severity of competition in such systems, and the ultimate impact on crop yield, is dependent upon the partitioning of resources, primarily of light and water, between the trees and crops. As yet, little research has been carried out in this field and the emphasis has been on positive interactions. As a fast growing, nitrogen-fixing tree species with good fodder value, leucaena has received a great deal of optimistic research attention, and has been studied for its diverse range of attributes, extending from its potential as a nitrogen source (Kang, 1981) to its role as a weed suppressant (Jama *et al.*, 1991). Singh *et al.* (1989) and Corlett *et al.* (1992a) attempted to separate above and below-ground interactions by using barriers to segregate crop and tree roots in a leucaena/millet system. Their work showed that interactions need not be positive and that above and below-ground competition may both be important and are likely to outweigh any microclimatic benefits.

A better mechanistic understanding of resource capture and utilisation in agroforestry systems is required to facilitate the development of improved systems in terms of species combinations, planting arrangements and management. The reductionist approach of this trial, involving a single tree-row rather than a full system, was chosen to enable both the

[1] Chapters 2 and 3 are drawn from Howard *et. al.*, (1995). Chapter 3 is largely unchanged; however additional information on materials and methods is provided in Chapter 2.

extent and nature of competition at the tree-crop interface to be determined.

3.2 LIGHT INTERCEPTION

In agroforestry systems, light interception by the crops is limited by the three factors, the duration of the crop canopy, its mean fractional interception and shading by the adjacent trees. The tree canopy is usually present throughout the season and, for a given age and size of tree, light interception is determined largely by planting arrangement (Table. 3.1).

Table 3.1 Seasonal fractional interception of PAR by maize and leucaena during the 1992 long rains. The last two columns represent the effective interception by the intercropped maize (i.e. the product of fractional interception by the maize and the fractional transmission by leucaena).

Treat.	tree/ crop	mean f_p	max. f_p	min. f_p	mean effective f_p	max. effective f_p
SM	maize	0.38	0.61	0	-	-
SMI	maize	0.45	0.67	0	-	-
LM	maize	0.28	0.42	0	0.21	0.31
LMI	maize	0.38	0.55	0	0.27	0.39
LM	leucaena	0.28	0.30	0.23	-	-
LMI	leucaena	0.35	0.37	0.29	-	-

Although the f_p values for maize were zero in all plots at the beginning of the season, the maximum values were approximately double those for the leucaena; seasonal mean f_p values for maize were also greater than for leucaena. The intercropped maize (LM and LMI) had an effective mean interception of little more than half that in the corresponding sole maize treatments (SM and SMI) due to a combination of reduced f_p and shading. Cumulative intercepted PAR was therefore initially greater for the leucaena in both LM

and LMI, but by the end of season the sole maize had intercepted >25 % more PAR than the intercropped trees and more than twice that of the intercropped maize in the LM plots. Taken together, interception by the maize and leucaena in LM was approximately 25 % greater than that of the sole maize, but the majority was intercepted by the tree component (Fig. 3.1).

3.3 LIGHT INTERCEPTION AND MAIZE DRY MATTER

During the same season (the 1992 long rains), an experiment was conducted at the same site in which maize was grown with and without irrigation under 75, 50, 25 and 0 % shade provided by shade-netting with neutral spectral qualities (Torquebiau, pers. comm.). A linear interpolation between these values was performed to provide a response curve for above-ground dry matter production by maize under 0-100 % shade. This was then used in conjunction with the seasonal mean value for the shade cast on each maize row (mean Tf_p for each row) to derive a predicted shade response for LM and LMI (Fig. 3.2, after ICRAF Annual Report, 1991). The shade response appeared to account for most of the reduction in yield in LMI, as might be expected since competition for water was largely eliminated by the application of irrigation. However, approximately 30 % of the reduction in maize yields in LM remains unexplained by the light response alone (Table 3.2). Further investigation of dry matter production shows that the seasonal dry matter:radiation quotient (e_p, sometimes referred to as the light use efficiency or conversion coefficient; Russell *et al.*, 1987) was remarkably constant for LM maize (Fig. 3.3) at 2.2 g MJ^{-1} (PAR). This is consistent with reported values for maize of 1.3 to 1.4 g MJ^{-1} for total radiation (Squire, 1990; Eq. 1.4, Section 1.4). The reduction in the LM maize yield not accounted for by the light response was probably due to a decrease in the seasonal mean value for f_p resulting from water stress rather than a reduction in e_p.

Harvest index

The overall mean harvest index (HI) was relatively constant across treatments (Table 3.2) but, when the row means for LM and LMI are considered, it is clear there was an abrupt inflection at around 300 g m^{-2}, below which HI decreased linearly with decreasing

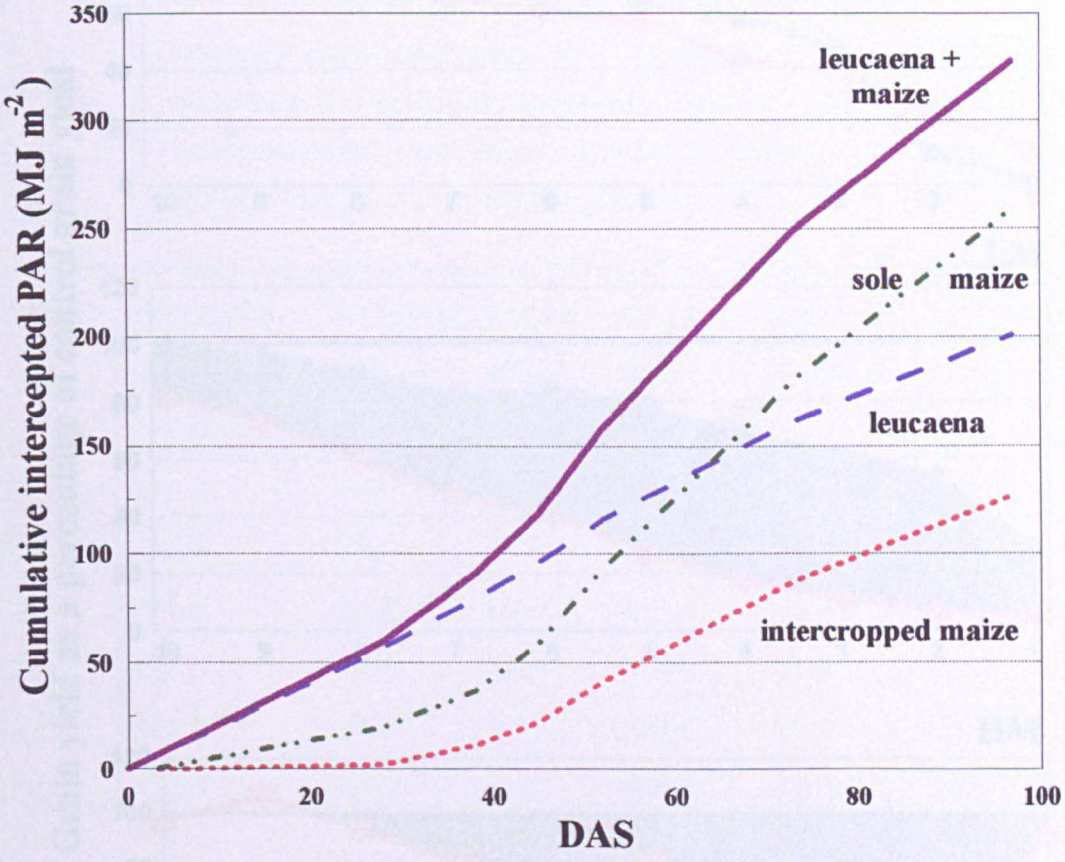


Figure 3.1 Cumulative interception of photosynthetically active radiation (PAR) by sole and intercropped maize, intercropped overstorey leucaena and the entire leucaena/maize agroforestry system, long rains 1992.

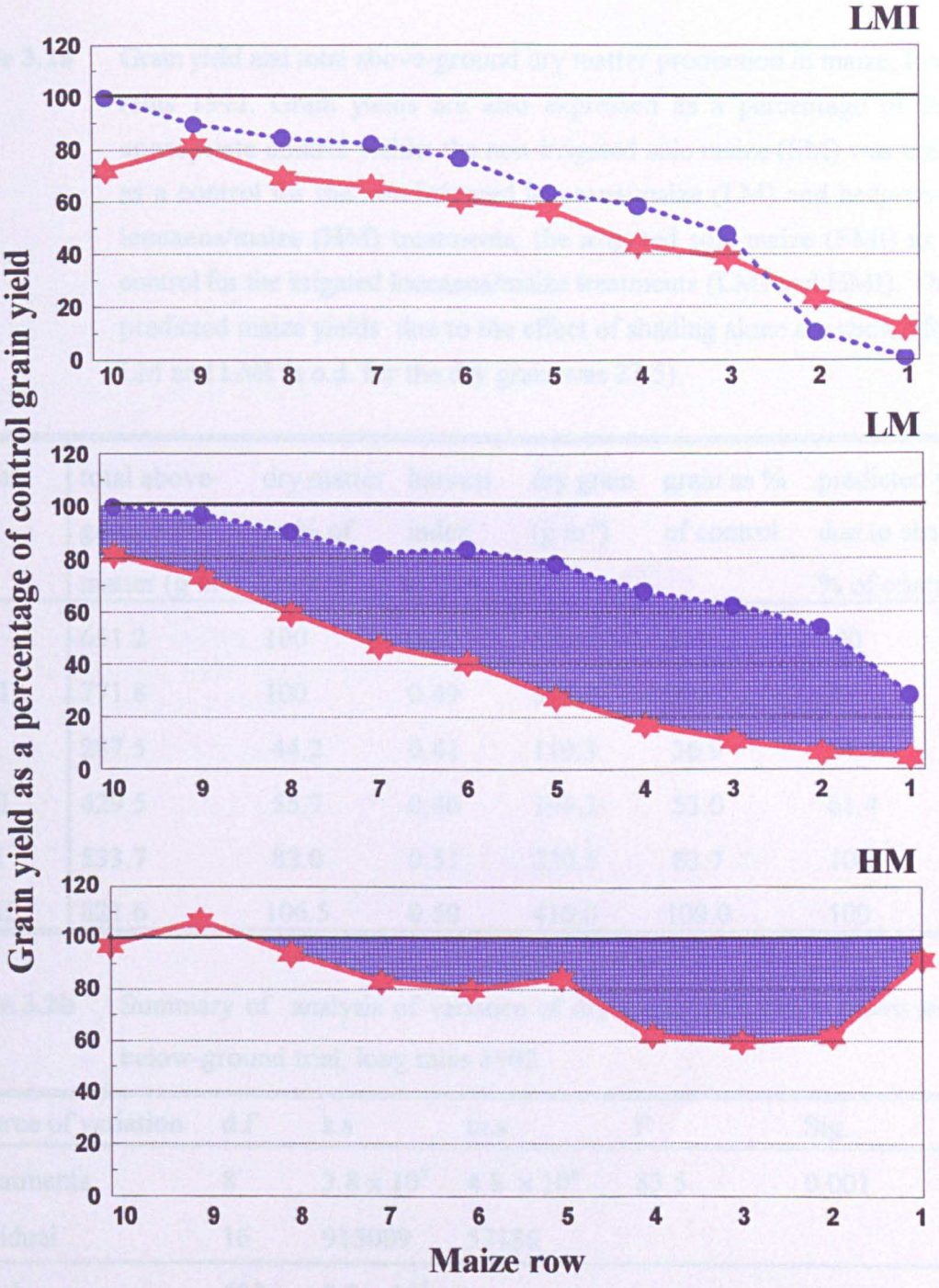


Figure 3.2 Mean row-by-row maize yield as a percentage of the appropriate control yields (✶). Non-irrigated sole maize was used as the control for the non-irrigated leucaena/maize (LM) and hedgerow leucaena/maize (HM) treatments, and irrigated sole maize as the control for the irrigated leucaena/maize (LMI). The predicted maize yields (●) resulting from the effect of shading alone are shown for LM and LMI. The shaded area indicates the estimated reduction in maize yield caused by competition with the leucaena for water. Row 1 is nearest to the tree/hedge, long rains 1992, Machakos, Kenya.

dry matter (Fig. 3.4). This probably occurred because drought and severe shading restricted the quantity of assimilates available for grain filling.

Table 3.2a Grain yield and total above-ground dry matter production in maize, long rains 1992. Grain yields are also expressed as a percentage of the appropriate control yields: the non-irrigated sole maize (SM) was used as a control for the non-irrigated leucaena/maize (LM) and hedgerow leucaena/maize (HM) treatments, the irrigated sole maize (SMI) as a control for the irrigated leucaena/maize treatments (LMI and HMI). The predicted maize yields due to the effect of shading alone are shown for LM and LMI (s.e.d. for the dry grain was 23.5).

Treat.	total above-ground dry matter ($g\ m^{-2}$)	dry matter as % of control	harvest index	dry grain ($g\ m^{-2}$)	grain as % of control	predicted yield due to shade as % of control
SM	651.2	100	0.50	323.1	100	100
SMI	771.8	100	0.49	376.1	100	100
LM	287.5	44.2	0.41	119.3	36.9	74.4
LMI	429.5	55.7	0.46	199.3	53.0	61.4
HM	533.7	82.0	0.51	270.5	83.7	100
HMI	821.6	106.5	0.50	410.0	109.0	100

Table 3.2b Summary of analysis of variance of dry grain yield in the above and below-ground trial, long rains 1992.

Source of variation	d.f	s.s	m.s	F	Sig.
Treatments	8	3.8×10^7	4.8×10^6	83.5	0.001
Residual	16	915089	57186		
Total	539	5.9×10^7			

NB. The analysis was performed at the level of individual maize rows for all ten treatments and the results are presented in summary form here. The mean yields of the other treatments not relevant to this study are not presented.

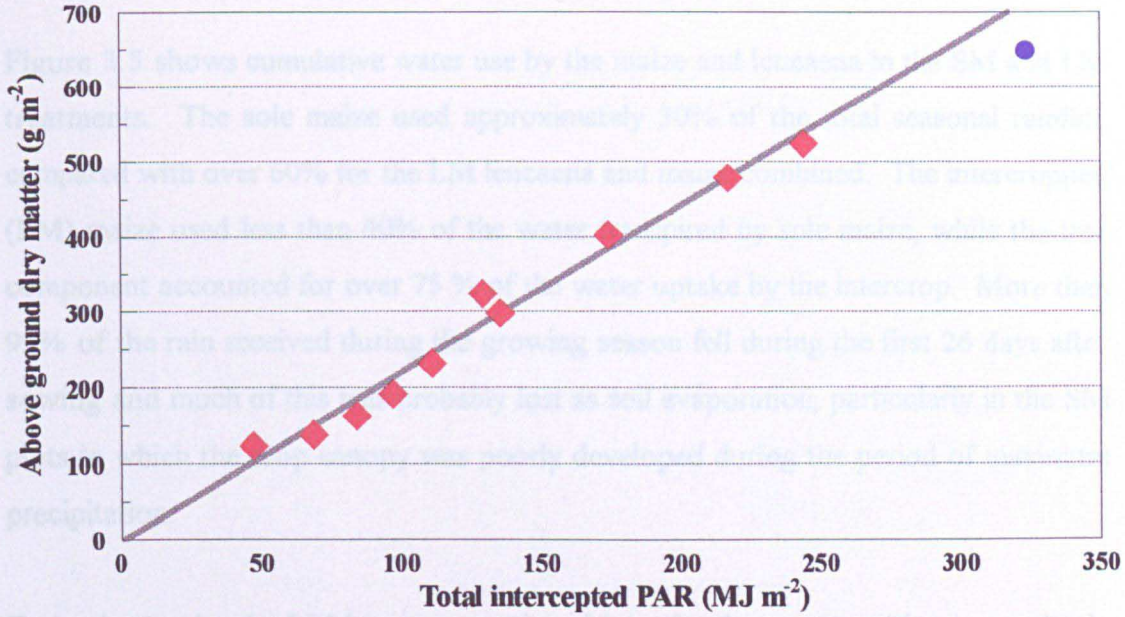


Figure 3.3 Relation between above-ground dry matter production and total intercepted photosynthetically active radiation (PAR). The values are the row means for the ten rows of maize in the leucaena/maize system (LM, ◆) and the overall mean for the sole maize (SM, ●).

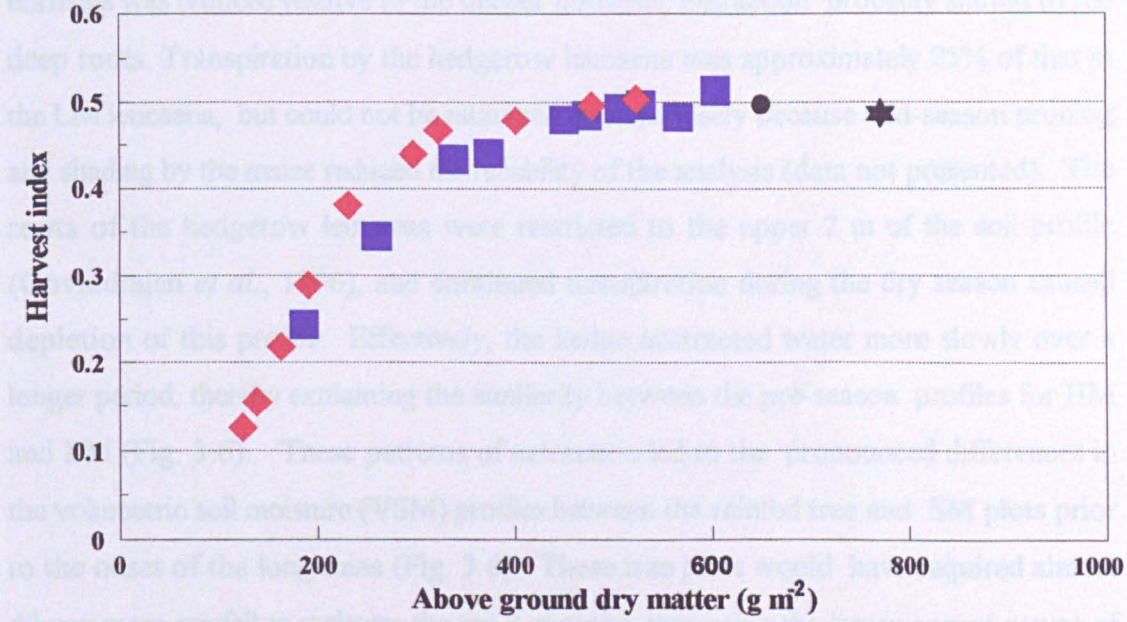


Figure 3.4 The relation between harvest index and above-ground dry matter production in maize. The data represent row means for the leucaena/maize (LM, ◆) and irrigated leucaena/maize (LMI, ■) treatments; the overall means for unirrigated sole maize (SM, ●) and irrigated sole maize (SMI, ✶) are also shown. Dry matter production and harvest index were lowest in maize rows nearest the tree rows, long rains 1992.

3.4 TRANSPIRATION AND SOIL MOISTURE

Figure 3.5 shows cumulative water use by the maize and leucaena in the SM and LM treatments. The sole maize used approximately 30% of the total seasonal rainfall, compared with over 60% for the LM leucaena and maize combined. The intercropped (LM) maize used less than 40% of the water transpired by sole maize, while the tree component accounted for over 75 % of the water uptake by the intercrop. More than 95% of the rain received during the growing season fell during the first 26 days after sowing and much of this was probably lost as soil evaporation, particularly in the SM plots in which the crop canopy was poorly developed during the period of maximum precipitation.

Transpiration by the LM leucaena continued into the dry season without completely depleting the upper 2 m of the soil profile. At this site, leucaena is probably an opportunistic water user since its highest rooting density was in the upper 50 cm of the profile but large roots penetrated below 2.5 m. Thus, when water availability in the upper horizons was reduced relative to the deeper horizons, extraction probably shifted to the deep roots. Transpiration by the hedgerow leucaena was approximately 25% of that in the LM leucaena, but could not be estimated more precisely because mid-season pruning and shading by the maize reduced the reliability of the analysis (data not presented). The roots of the hedgerow leucaena were restricted to the upper 2 m of the soil profile (Govindrajan *et al.*, 1996), and continued transpiration during the dry season caused depletion of this profile. Effectively, the hedge abstracted water more slowly over a longer period, thereby explaining the similarity between the pre-season profiles for HM and LM (Fig. 3.6). These patterns of extraction led to the pronounced differences in the volumetric soil moisture (VSM) profiles between the rainfed tree and SM plots prior to the onset of the long rains (Fig. 3.6). These tree plots would have required almost 40 mm more rainfall to recharge the top 2 m alone, indicating the interseasonal nature of competition. The greater soil moisture depletion at 50 DAS in the plots containing trees would have been a function of both the differing recharge requirements and the greatest extraction rates of the trees.

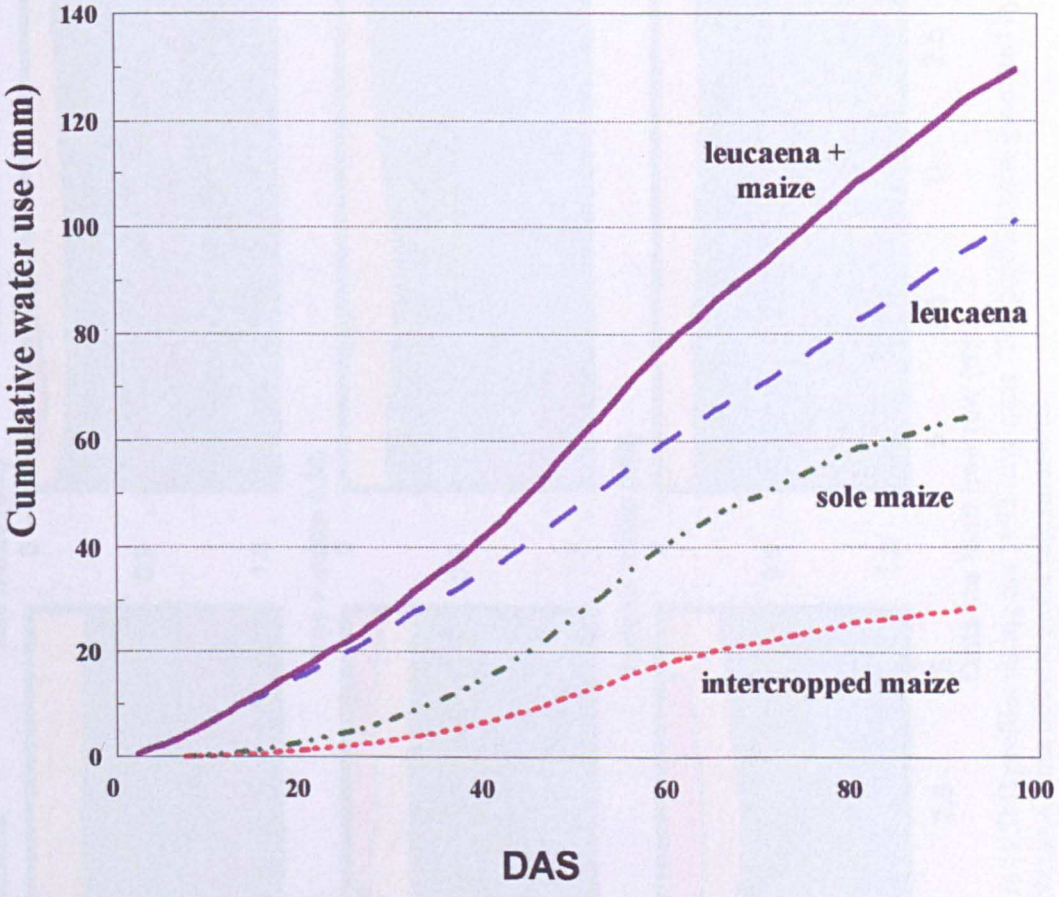


Figure 3.5 Cumulative water use by sole and intercropped maize, intercropped overstorey leucaena and the entire leucaena/maize agroforestry system, long rains 1992.

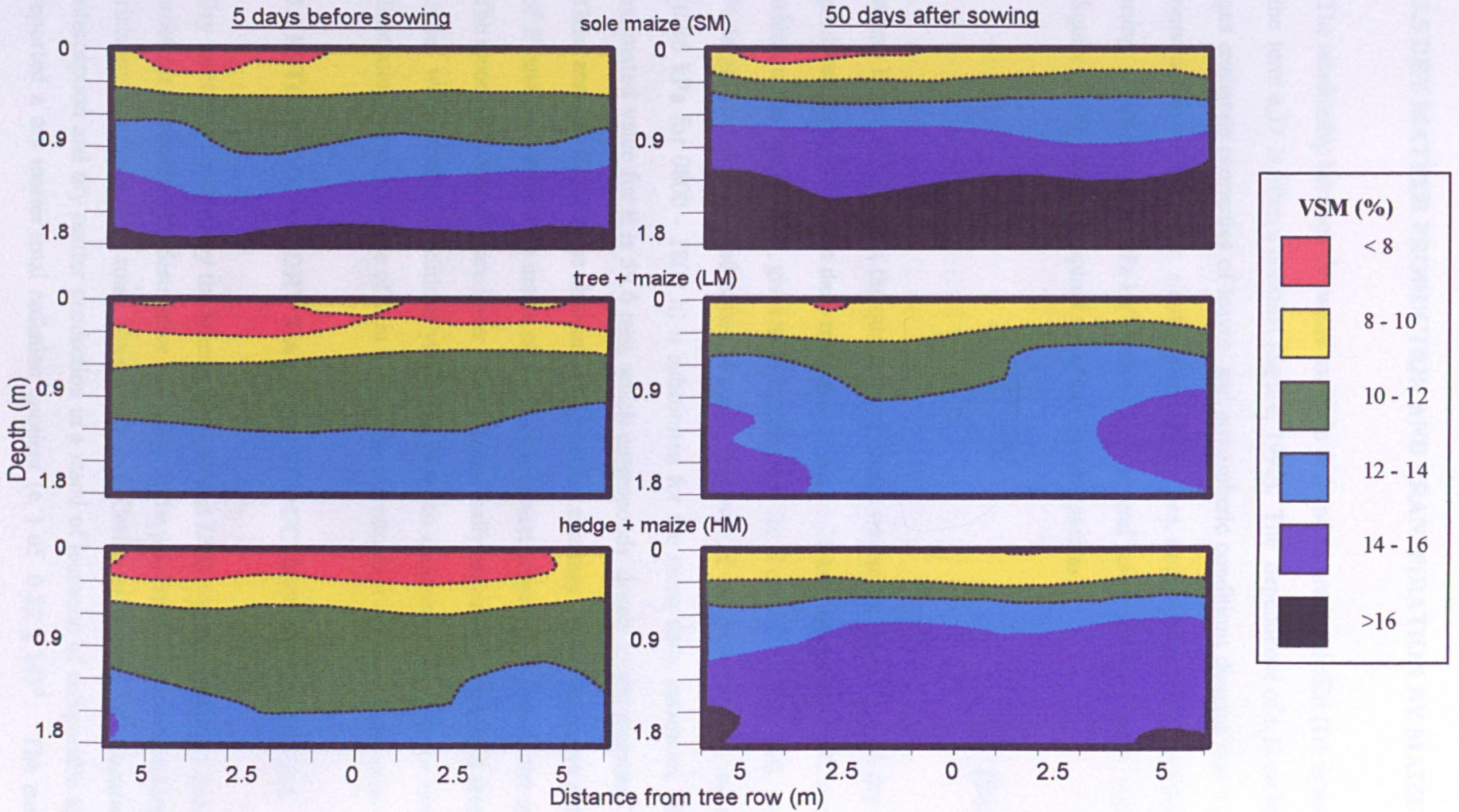


Figure 3.6 Volumetric soil moisture (VSM) profiles during the 1992 long rains. The profiles were generated by a spline interpolation of an 8 by 12 matrix obtained from neutron probe measurements.

3.5 DRY MATTER PRODUCTION AND TRANSPIRATION BY MAIZE

The relationship between the water use ratio (e_w) and saturation deficit (D) is such that the term e_wD is often a constant (Squire, 1990). The dependence of e_wD on both the gas exchange properties of leaves and atmospheric conditions dictates that it should remain near-constant for similar groups of species, such as tropical C4 cereals. Thus, using a mean of 9.4 g kPa kg^{-1} derived from several values for pearl millet, quoted by Squire (1990), total transpired water can be estimated as:

$$E = \frac{(W \times D)}{(e_w D)} \qquad \textbf{(Eq. 3.1)}$$

where E and W represent the quantities of water transpired (kg m^{-2}) and dry matter produced (kg m^{-2}). Mean daily maximum D was 1.28 kPa during the 1992 long rains which, using Equation 3.1, gives an estimated value for E of 88.7 mm for SM, some 30 % larger than the measured value (64 mm). However, if the mean daytime value for D (0.86 kPa for 0800 - 1800 h) is substituted for the mean daily maximum, then the estimated value for E is 59.6 mm, which corresponds closely to the measured value. These analyses illustrate the alternative approaches that may be used to derive estimates of E and the conservative nature of certain biophysical properties across similar species. The recorded values of D are lower than those normally expected in semi-arid areas, and under water-limited conditions yields are likely to decrease linearly as D increases, illustrating the importance of D in limiting crop production in this climatic zone.

3.6 ESTIMATION OF DRY MATTER PRODUCTION BY LEUCAENA

Dry matter production by the leucaena in LM and LMI was not measured due to the problems associated with destructive sampling of the perennial component in long-term trials involving relatively small plots. However, Corlett *et al.* (1992b) measured light interception and dry matter production in a stand of leucaena of comparable age and reported a dry matter:total radiation quotient (e_t) of 0.82 g MJ^{-1}. The empirical

relationship of Squire (1990):

$$\ln(1-f_p) = 1.4\ln(1-f_t) \qquad \textbf{(Eq. 3.2)}$$

where f_t is the fractional interception of total radiation, permits this e_t value to be converted to an e_p of 1.32 g MJ^{-1} for PAR. This value can in turn be used to provide estimates of dry matter production of 264 and 333 g m^{-2} for the leucaena in LM and LMI using the relationship:

$$W=e_p\Sigma S_p \qquad \textbf{(Eq. 3.3)}$$

where $\sum S_p$ represents total cumulative intercepted PAR (MJ m^{-2}; after Squire, 1990). Although these estimates of dry matter production by leucaena were derived using a value of e_p for a different site and season, they can be corroborated to some extent using the derived value for W obtained for LM in Equation 3.1. This gives a value for $e_w D$ of 3.4 g kPa kg^{-1} for the LM leucaena, well within the expected range for C3 plants (Squire, 1990), suggesting that the estimates of dry matter production for leucaena are of the correct order. Figure 3.7 shows daytime trends for D and transpiration by leucaena, in which the maximum rates of transpiration occurred during the period of maximum D, indicating that e_w might have been lower than if maximum transpiration had occurred asynchronously with maximum D.

Addition of the estimated dry matter production by leucaena to the corresponding measured above-ground values for maize suggests that total seasonal above-ground dry matter production was 552 and 762 g m^{-2} in LM and LMI respectively. The irrigated and non-irrigated tree/crop systems both produced less total dry matter than the respective sole maize controls, although this conclusion would no longer apply if tree growth during the dry season was included.

3.7 DISCUSSION

Total intercepted PAR was 327 and 413 MJ m^{-2} in LM and LMI, compared with 258 and 307 MJ m^{-2} in the SM and SMI sole maize treatments. However, little more than 30 % of the light intercepted by LM and LMI was captured by the crop component and

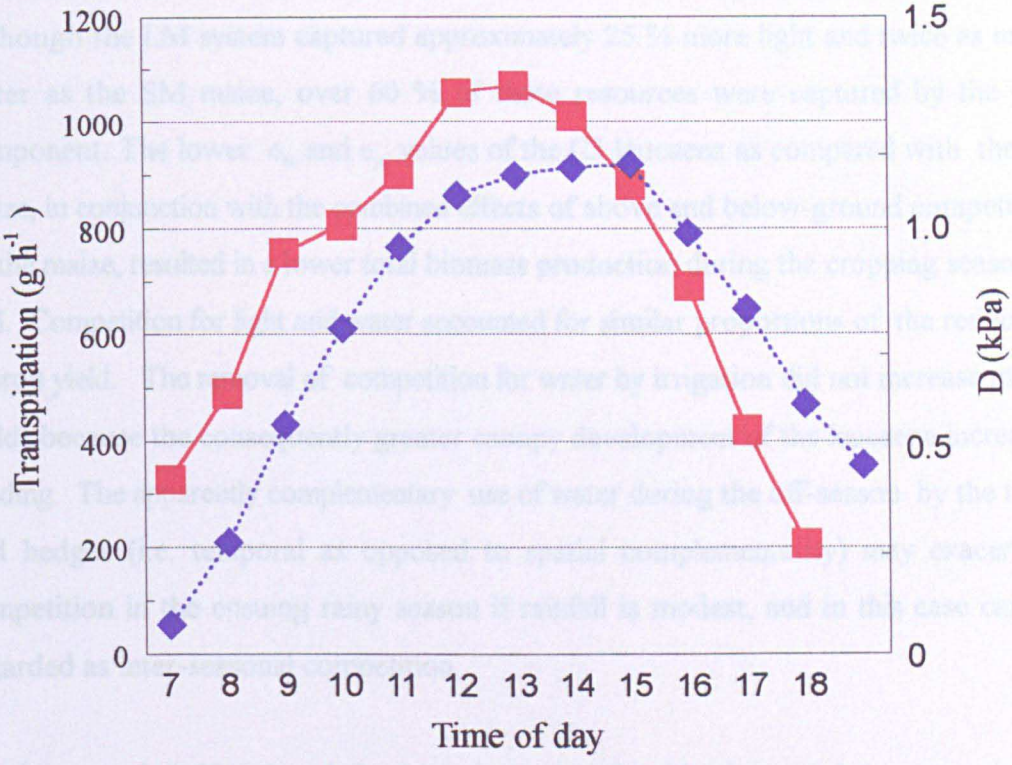


Figure 3.7 Daytime trends in saturation vapour pressure deficit (◆, D) and leucaena transpiration (■) during the 1992 long rains.

competition for light alone was found to reduce maize yields by more than 30 %. Total water uptake by the LM leucaena and maize accounted for 60 % of the seasonal rainfall (237 mm), compared to 30 % in the sole maize. However, as for light interception, only 30 % of the water use in LM was by the intercropped maize, and competition from the trees for soil water reduced maize yields over 6 m away from the leucaena.

Although the LM system captured approximately 25 % more light and twice as much water as the SM maize, over 60 % of these resources were captured by the tree component. The lower e_w and e_p values of the C3 leucaena as compared with the C4 maize, in conjunction with the combined effects of above and below-ground competition on the maize, resulted in a lower total biomass production during the cropping season in LM. Competition for light and water accounted for similar proportions of the reduction in crop yield. The removal of competition for water by irrigation did not increase maize yields because the consequently greater canopy development of the leucaena increased shading. The apparently complementary use of water during the off-season by the trees and hedges (i.e. temporal as opposed to spatial complementarity) may exacerbate competition in the ensuing rainy season if rainfall is modest, and in this case can be regarded as inter-seasonal competition.

Eastham *et al.* (1990) found that higher planting densities increased the extraction of water at depth in some tree species. Thus, it is possible that higher planting densities of leucaena in this or similar environments would result in a highly effective capture of water, as well a substantial increase in fractional light interception. In the leucaena/maize systems examined here, the leucaena proved to be more effective at resource capture, yet less efficient in resource utilisation since it exhibited a lower dry matter:radiation quotient and a lower transpired water:dry matter ratio than maize. Thus the leucaena in the agroforestry systems captured more of the resources that could have been used more effectively by the maize, causing the performance of the mixture to be sub-optimal; these results suggest that the two components would be best grown separately. A similar conclusion was reached by Singh *et al.* (1989) and Corlett *et al.* (1992a), who found that above and below-ground competition between the components of a leucaena/millet alley-cropping system resulted in sub-optimal resource capture and utilisation.

Agroforestry combinations containing C4 species should focus on appropriate management of the woody component to minimise competition for light during the growing season, thereby permitting most of the light to be captured by the more efficient utiliser of this resource. In water-limited environments, trees such as leucaena, which rapidly deplete the crop rooting zone of water, should be avoided and greater emphasis placed on deeper rooting species which exploit a different part of the resource base. There is also a need for further research into agroforestry systems involving shade tolerant C3 crop species, as well as the potentially more complex task of establishing the mechanisms that govern the rooting patterns and behaviour of tree roots.

COMPLEMENTARITY IN RESOURCE USE ON SLOPING LAND

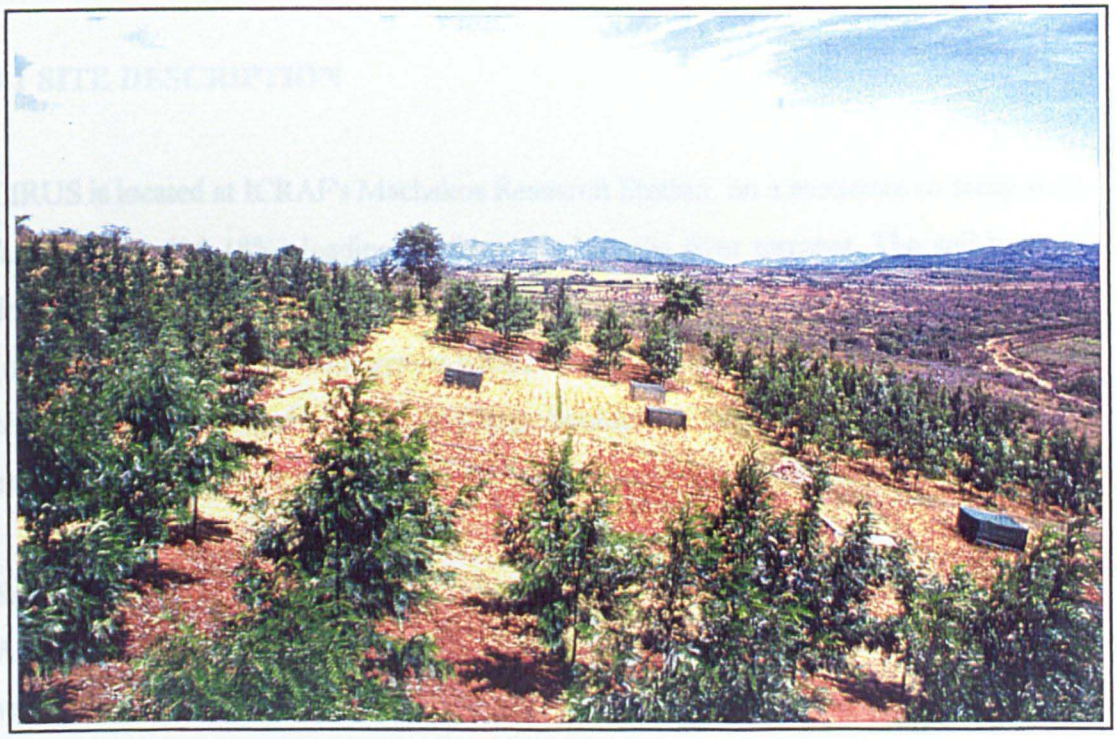


Plate 3 CIRUS during the final harvest of the 1992/3 short rains.

CHAPTER 4

EXPERIMENTAL METHODS AND MEASUREMENTS: 2

Chapters 2 and 3 describing the experimental programme and results from the Above and Below Ground Competition (ABG) trial formed the first section of this thesis. Chapters 4 to 7 describing similar studies in the Complementarity In Resource Use on Sloping land (CIRUS) trial form the second (and major) section of the thesis. Chapter 4 describes those methods used in CIRUS which were not discussed in Chapter 2.

4.1 SITE DESCRIPTION

CIRUS is located at ICRAF's Machakos Research Station, on a moderate to steep west-facing slope (16-18%) leading up from the Maruba river terraces. The soil is a well drained, shallow to moderately deep (0-2.5 m) sandy clay loam overlying petroplinthite (murram), and is stony with gravel bands. The land had no previous known cropping history and was cleared of scrub and large boulders in July 1991. Soil preparation was immediately undertaken by hand and the trees and crops were planted in October 1991.

Soil depth

As irregularity in soil depth was suspected to be responsible for the observed localised variation in crop growth within treatments, an extensive soil depth survey was undertaken in February 1993. The trial was marked out with a 40 x 40 m grid and the position of each experimental plot recorded relative to each square. The grid squares were then sub-divided into smaller 4 x 4 m grid squares and a 5 cm diameter auger was used to determine soil depth at each of the intersections of the lines forming the smaller grid. If soil depth differed markedly from adjacent sampling points, an additional measurement was made 20 - 30 cm away to reduce the risk that the true soil depth would be underestimated due to the presence of erratic rocks within the profile. A 4 x 4 m grid was chosen to provide sufficient resolution to determine the extent of variations in mean plot depth, while avoiding a prohibitive number of sampling points. Figure 4.1 shows the results of the survey and clearly illustrates the highly variable nature of the sub-surface

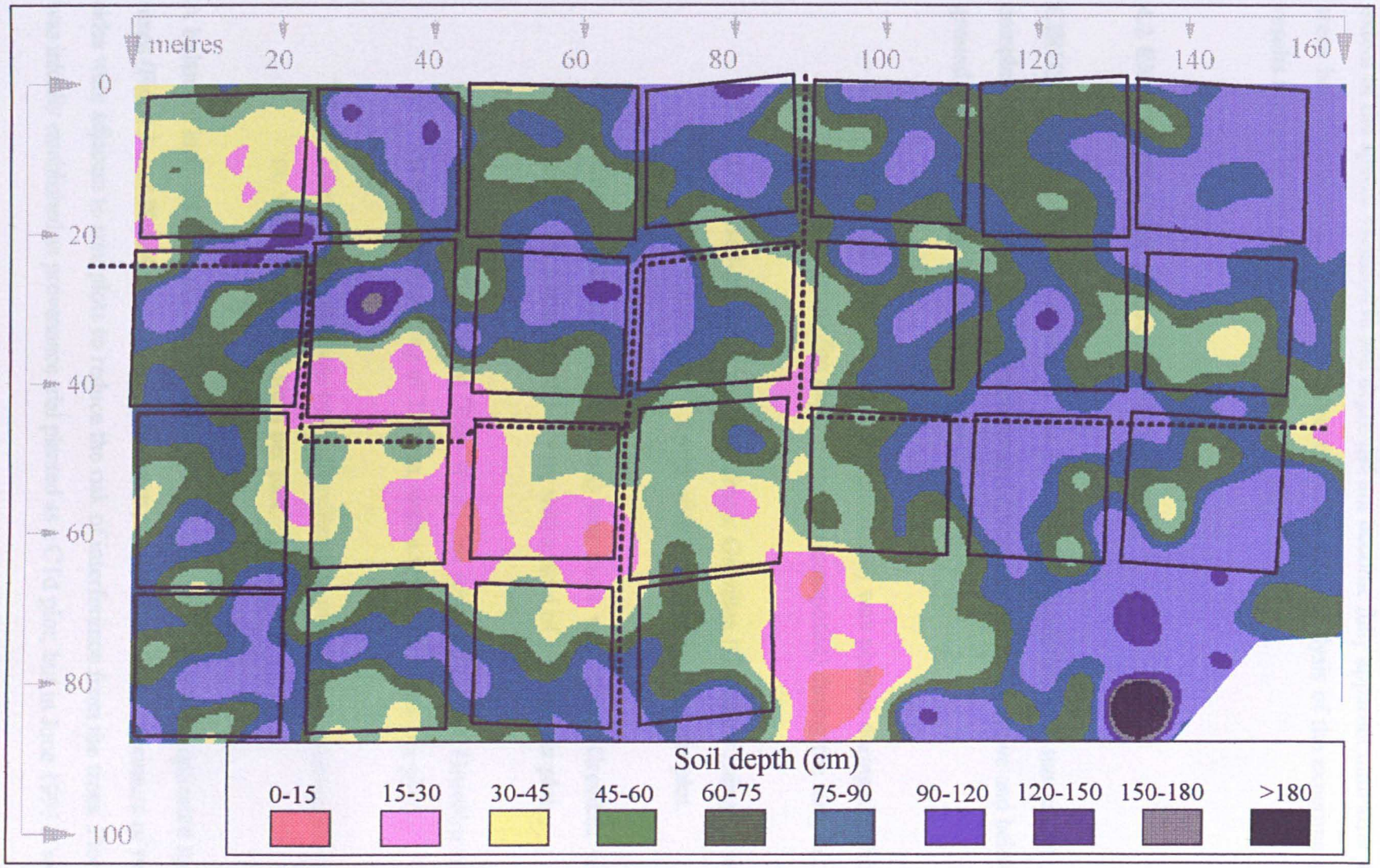


Figure 4.1 Soil depth in the CIRUS; boxes denote plot boundaries and dotted lines represent block boundaries.

topography. Ideally, such soil surveys should be carried out prior to trial establishment and local variations in soil depth accounted for in the experimental design. However, the extent of the spatial variation in soil depth did not become fully apparent until after the trees had been planted and so was incorporated into the analysis of the experimental results instead of the experimental design (cf. Section 4.5).

4.2 EXPERIMENTAL DESIGN AND LAYOUT

CIRUS was designed to investigate the effects of competition and the extent of complementarity between *Grevillea robusta* and associated crops for above and below-ground resources using the following treatments (Fig. 4.2):

Cg - Sole crop. Cowpea (*Vigna unguiculata*) was planted during the short rains and maize (*Zea mays*, Katumani composite) during the long rains.

CTd - Dispersed-planted trees with crops. Grevillea (*Grevillea robusta*) was planted at a spacing of 3 x 4 m, with a total of 35 trees per plot.

CTc - Contour-planted (North-South) tree rows with crops. Grevillea was planted at a spacing of 2 x 9 m, with a total of 30 trees per plot.

CTa - Across contour planted (East-West) tree rows with crops. Grevillea was planted at a spacing of 2 x 9 m, with a total of 30 trees per plot.

Td - Dispersed-planted sole trees. Grevillea was planted at a spacing of 3 x 4 m, with a total of 35 trees per plot.

A balanced incomplete block design was used and each treatment was replicated four times (Fig. 4.3 and Plate 4.1). Sole crop plots were positioned so that a maximum of two sides were adjacent to tree plots to reduce the risk of interference from the trees. Plot 1 was initially established as provenance trial planted as a CTd plot, but in June 1993 it was

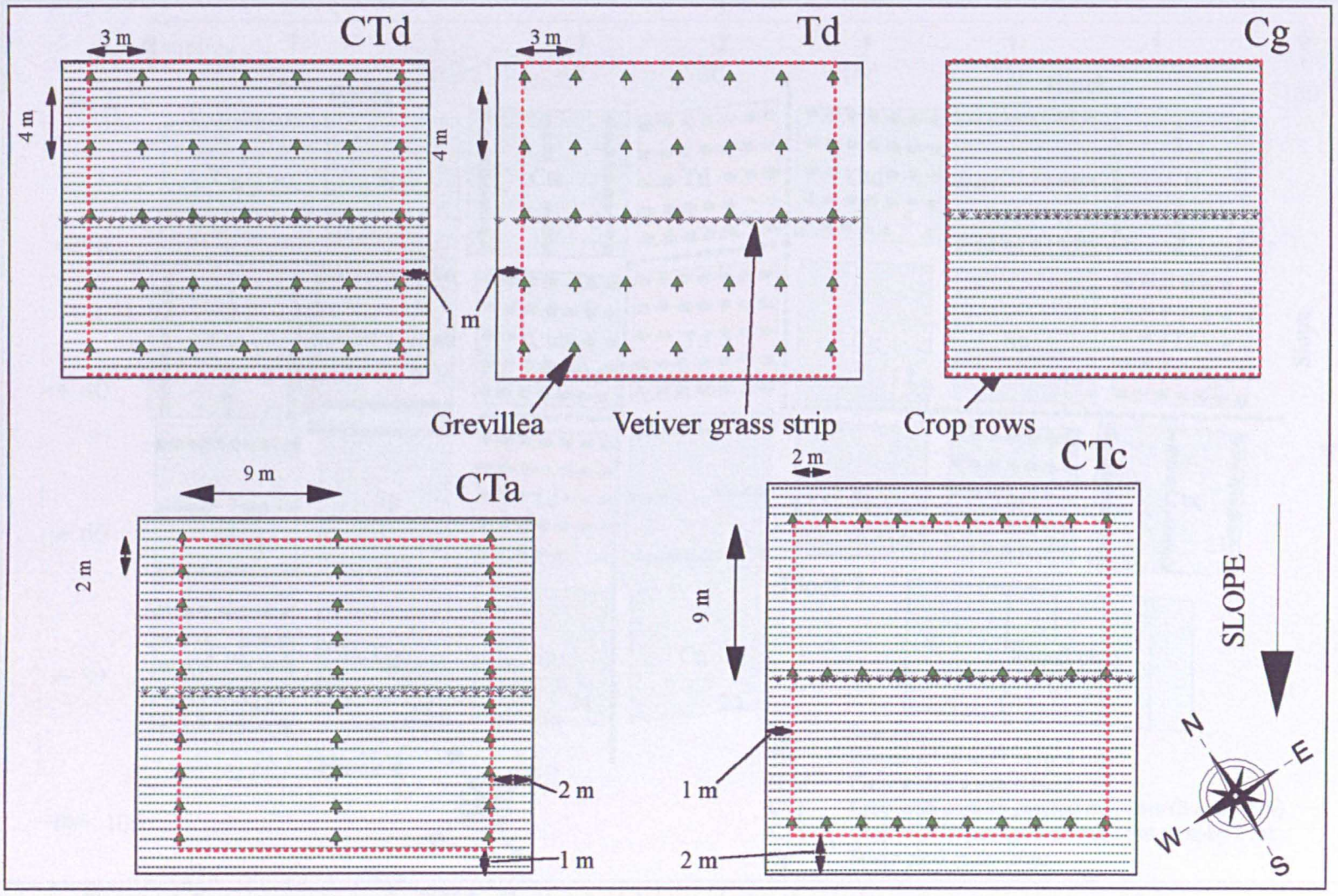


Figure 4.2 Plot layouts of treatments in CIRUS; the red dashed squares indicate the 18 x 18 m size of the sole crop plots for comparison.

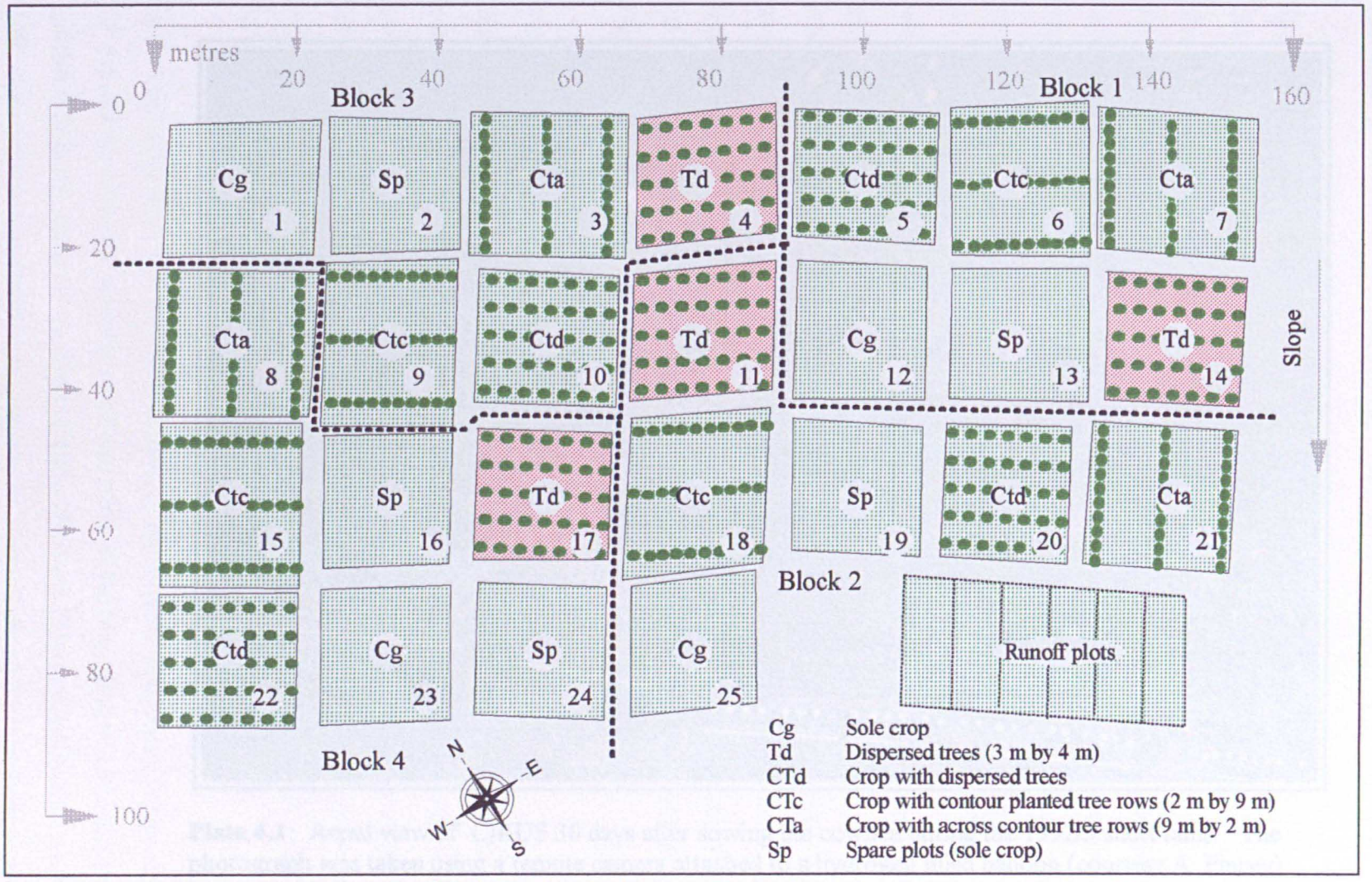


Figure 4.3 Experimental layout for CIRUS. The rhomboidal shape of some plots is due to the contour planting of the tree rows and the extension of plot edges adjacent to tree rows.

Plate 4.1 Aerial view of CIRUS 30 days after sowing the cowpea during the 1992/3 short rains. The photograph was taken using a remote camera attached to a hydrogen filled balloon (courtesy A. Pinney).

decided to remove the grevillea from this plot to provide an additional Cg plot free from potential interference from grevillea in adjacent plots and permit destructive sampling of grevillea.

Plot size and grass strips

The leucaena/maize system described in Section 2.2 was cropped between the plots to provide guard areas, but in CIRUS the plots were separated by grass walkways to reduce the risk of erosion and facilitate access. The plots were initially 18 x 18 m in area, but those containing trees were extended by 1 m adjacent to the tree rows in September 1992 and by a further 1 m in February 1993 to reduce the risk of competition between the grass and the trees; this accounts for the rhomboidal shape of some plots (Figs. 4.2 and 4.3, and Plate 4.1). Due to the potential for erosion on sloping land, a vetiver grass strip was contour-planted in the centre of each plot and the crop and tree rows were planted parallel to this. The grass walkways and vetiver strips were cut at 7-14 day intervals to minimise competition with adjacent trees and crops, and after establishment the vetiver grass was maintained at a height of 10-15 cm. Six runoff plots were established in September 1993, three with and three without vetiver strips to investigate their influence on runoff, soil erosion and crop growth. The runoff plots were treated separately from the main experiment for the purpose of analysis.

Tree and crop planting and trial management

Table 4.1 shows the planting and management schedule for CIRUS. Grevillea was established by planting three month old seedlings and the trees were periodically side-pruned from the base of the stem upwards to encourage the production of straight single stems (Section 4.3). The development of lateral roots by grevillea was examined before every rainy season to ensure that tree roots had not extended into adjacent plots. No fertilisers were applied and no residues were incorporated into the soil.

In the short rains of 1991/2 and 1992/3, cowpea was planted at an inter-row spacing of 75 cm and an intra-row spacing of 18 cm, while in the long rains of 1992 maize was planted at inter and intra-row spacings of 100 and 30 cm. However, in the short rains of 1993/4, the cowpea were planted at a spacing of 50 by 12 cm so that the rows would be

in phase with the maize rows during subsequent seasons (i.e. alternate cowpea rows occupied the same positions as the maize rows). It was necessary for the two crops to have spatially compatible planting arrangements so that equipment such as tensiometers and neutron probe access tubes could be left permanently installed. Maize was planted in the long rains of 1993, but germination and establishment were extremely poor due to the failure of the rains after initial receipts of ≈35 mm; the plants were removed when they became irreversibly wilted 20 days after emergence.

Table 4.1. Planting and management schedule for CIRUS; DAP denote days after planting the grevillea.

Date	DAP	Task
15/10/91	1	Mean tree planting date *
12/11/91	29	Cowpea sown - short rains 1991/2
21/02/92	130	Cowpea harvest
11/04/92	180	Maize sown - long rains 1992
24/08/92	315	Maize harvest
01/09/92	323	Plots extended by 1 m adjacent to tree rows
05/11/92	388	Cowpea sown - short rains 1992/3
12/02/93	487	Cowpea harvest
15/02/93	490	Plots extended a further 1 m adjacent to tree rows
27/02/93	502	Soil depth survey
01/04/93	535	Maize season failed - long rains 1993
06/06/93	601	First grevillea pruning
22/06/93	617	Plot 1 provenance trial cleared
01/09/93	688	Runoff plots cleared
01/11/93	749	Cowpea sown - short rains 1993/4
04/02/94	844	Cowpea harvest
23/02/94	863	Second grevillea pruning
Fortnightly - weekly		Vetiver grass strips cut to 10 - 15 cm
		Grass walkways cut to < 5 cm
		Plots weeded (monthly during the dry season)

* The date shown represents the mean planting date, since planting extended over several days.

4.3 CLIMATE DATA

Climate data were initially collected using a Campbell automatic weather station and CR7 data logger, located on an exposed site at the top of the slope 300 m north-west of CIRUS. In October 1992 a Delta-T automatic weather station was installed approximately 400 m to the west of the Campbell station and in December 1993 an 8 m tower was installed in the centre of CIRUS and the Campbell station was relocated on top of this to provide more reliable site-specific data. The data from the Campbell system were used for all calculations except for radiation data (see global radiation below) to ensure continuity.

Global radiation

Due to the re-siting of the Campbell weather station and the subsequent temporary unreliability of the radiation sensor, global radiation values for some of the period between December 1993 and early February 1994 were calculated using data from the Delta-T weather station. As the radiation sensor in the Delta-T system is known to be over-sensitive at higher altitudes (Khan, pers. comm.), the following relationship was derived from the hourly values for the two month period prior to December 1993, when both sensors were operational:

$$G_c = aG_\Delta \qquad \textbf{(Eq. 4.1)}$$

where G_c and G_Δ are the global radiation values provided by the Campbell and Delta-T weather stations respectively, and a is 0.8539 (s.e. = 0.0025, $r^2 = 0.98$, n =793). Values from the Delta-T system for the period between December 1993 and early February 1994 were used to estimate the equivalent Campbell values using Equation 4.1.

4.4 GROWTH ANALYSIS AND PRUNING OF GREVILLEA

The use of destructive sampling methods for the growth analysis of trees in long term agroforestry trials is only possible if the experiments are large enough to provide sufficient trees for analysis over extended periods. When the duration of the trial is likely to exceed five years and there are only 30 or 35 trees per plot, as in CIRUS, regular destructive sampling is clearly impossible and alternative methods must be employed. When the provenance trial was cleared from plot 1 on 22 June 1993, the height, basal diameter, number of leaves and the fresh and dry weights of stems, branches and leaves were recorded for each tree. The same information (except for stem weight) was recorded on both occasions when the trees in the main trial were pruned. On 6-7 June 1993, the trees were side-pruned to maintain a regular canopy structure and encourage apical dominance; some of the longer branches were only partially pruned to confer a more uniform canopy shape (Fig. 4.4). Pruning was repeated on 23-25 February 1994, except that predominantly entire branches were removed. The height and basal diameter of all trees were measured at monthly intervals and the values obtained were used in conjunction with the data from the prunings and clearance of the provenance trial to estimate leaf, stem and branch biomass and leaf area.

Wood density

After pruning in February 1994, sections of branch and stem were cut into smaller segments (< 20 cm in length). These were then immersed in water in a 200 ml measuring cylinder (500 ml for larger samples) using a thin piece of wire (of negligible volume) and their volume was determined as the volume of water displaced. The sections were then oven-dried to constant weight at 60 °C. Regression analysis of volume against dry weight was performed, giving the following equation:

$$W = aV \qquad \textbf{(Eq. 4.2)}$$

where W and V represent dry weight (g) and volume (cm^3) and a = 0.469 (s.e. 0.006; r^2 = 0.995, 8 d.f., $p < 0.001$). Figure 4.5 shows that there was a close linear correlation between dry weight and volume for both branch and stem segments; a constant value for the density of woody tissues in grevillea of 0.469 g cm^{-3} was therefore assumed.

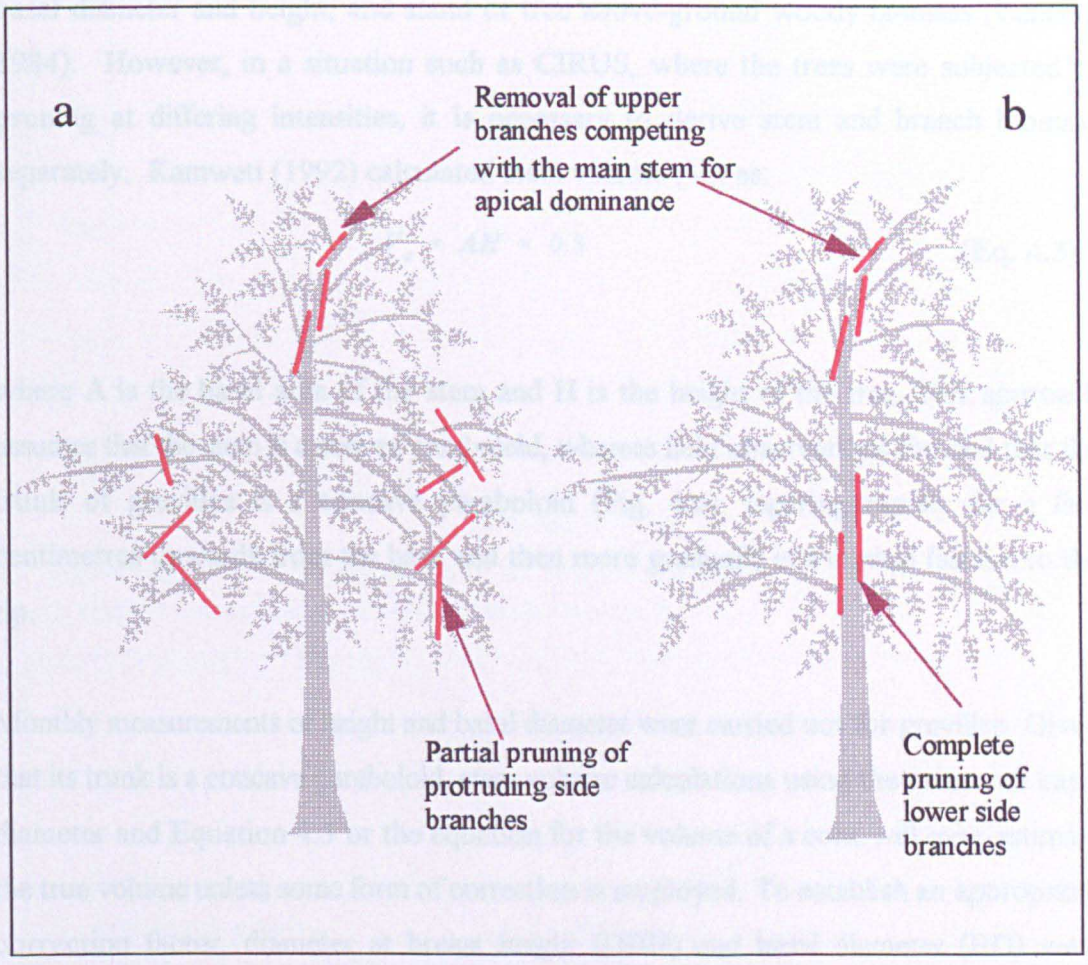


Figure 4.4 Pruning of grevillea in CIRUS: (a) and (b) show the methods adopted during the first and second prunings (6 June1993 and 23 February 1994).

Stem volume

There have been several studies of the relationship between tree allometrics, typically basal diameter and height, and stand or tree above-ground woody biomass (Cannell, 1984). However, in a situation such as CIRUS, where the trees were subjected to pruning at differing intensities, it is necessary to derive stem and branch biomass separately. Kamweti (1992) calculated stem volume (V_s) as:

$$V_s = AH \times 0.5 \qquad \textbf{(Eq. 4.3)}$$

where A is the basal area of the stem and H is the height of the tree. This approach assumes that the stem is a convex paraboloid, whereas field observations showed that the trunk of grevillea is a concave paraboloid (Fig. 4.6), tapering rapidly for a few centimetres upwards from the base and then more gradually in a conical fashion to the tip.

Monthly measurements of height and basal diameter were carried out for grevillea. Given that its trunk is a concave paraboloid, stem volume calculations using the measured basal diameter and Equation 4.3 or the equation for the volume of a cone will over-estimate the true volume unless some form of correction is employed. To establish an appropriate correction factor, diameter at breast height (DBH) and basal diameter (BD) were measured concurrently prior to the removal of the provenance trial and also on 28 March 1994 in the main trial. An estimated basal diameter (BD_{est}) can be calculated from DBH if the tree height (H) is known and the stem is assumed to be conical (Fig. 4.6) using ratios of similar triangles as follows:

$$\frac{BD_{est}}{DBH} = \frac{H}{(H-BH)}$$

$$\therefore \quad BD_{est} = DBH \times \frac{H}{(H-BH)} \qquad \textbf{(Eq. 4.4)}$$

where BH is breast height (130 cm). If stem volume is calculated using BD and the equation for the volume of a cone, the ratio BD_{est}:BD can be used as a correction factor for the concave paraboloid form as follows:

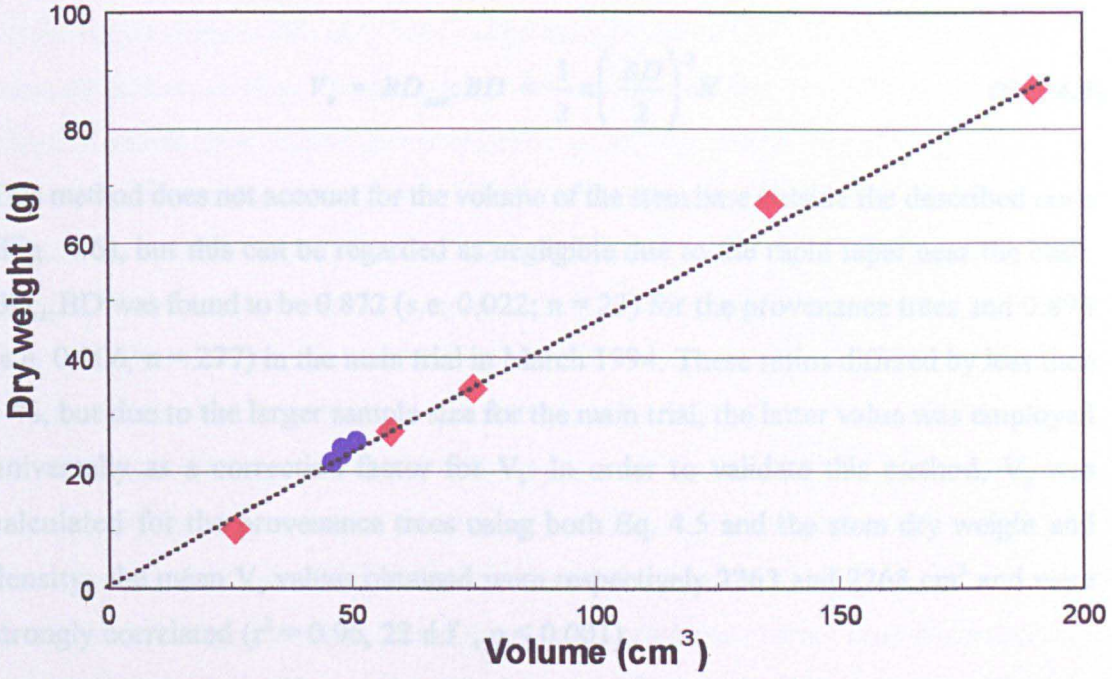


Figure 4.5 Relationship between dry weight and volume for sections of grevillea stems (◆) and branches (●). The regression line is $y = 0.469x$ ($r^2 = 0.995$).

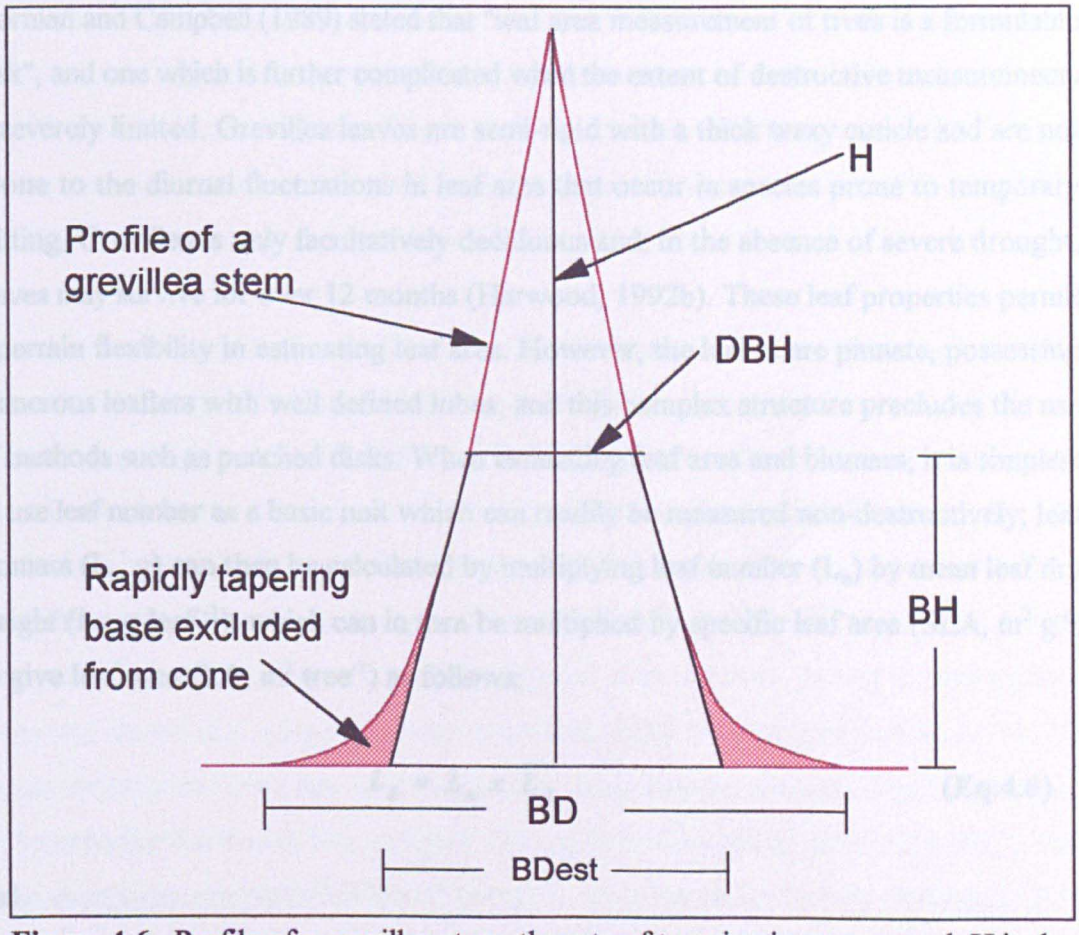


Figure 4.6 Profile of a grevillea stem: the rate of tapering is exaggerated. H is the height of the tree, BH is breast height (1.3 m), DBH is the diameter of the stem at breast height, BD is the basal diameter of the stem and BDest is the basal diameter estimated from DBH and H when the stem is assumed to be conical.

$$V_s = BD_{est}:BD \times \frac{1}{3}\pi\left(\frac{BD}{2}\right)^2 H \qquad \textbf{(Eq. 4.5)}$$

This method does not account for the volume of the stem base outside the described cone (Fig. 4.6), but this can be regarded as negligible due to the rapid taper near the base. BD_{est}:BD was found to be 0.872 (s.e. 0.022; n = 23) for the provenance trees and 0.878 (s.e. 0.006, n = 277) in the main trial in March 1994. These ratios differed by less than 1 %, but due to the larger sample size for the main trial, the latter value was employed universally as a correction factor for V_s. In order to validate this method, V_s was calculated for the provenance trees using both Eq. 4.5 and the stem dry weight and density; the mean V_s values obtained were respectively 2263 and 2268 cm^3 and were strongly correlated ($r^2 = 0.96$, 22 d.f. , $p < 0.001$).

Leaf number, area and biomass

Norman and Campbell (1989) stated that "leaf area measurement of trees is a formidable task", and one which is further complicated when the extent of destructive measurements is severely limited. Grevillea leaves are semi-rigid with a thick waxy cuticle and are not prone to the diurnal fluctuations in leaf area that occur in species prone to temporary wilting. Grevillea is only facultatively deciduous and, in the absence of severe drought, leaves may survive for over 12 months (Harwood, 1992b). These leaf properties permit a certain flexibility in estimating leaf area. However, the leaves are pinnate, possessing numerous leaflets with well defined lobes, and this complex structure precludes the use of methods such as punched disks. When estimating leaf area and biomass, it is simplest to use leaf number as a basic unit which can readily be measured non-destructively; leaf biomass (L_b, g) can then be calculated by multiplying leaf number (L_n) by mean leaf dry weight (L_d, g $leaf^{-1}$), which can in turn be multiplied by specific leaf area (SLA, $m^2\ g^{-1}$) to give leaf area (LA, $m^2\ tree^{-1}$) as follows:

$$L_b = L_n \times \overline{L_d} \qquad \textbf{(Eq.4.6)}$$

and

$$LA = L_b \times SLA \qquad \textbf{(Eq.4.7)}$$

At the final pruning in February 1994, subsamples of up to 1000 grevillea leaves per plot were taken from all plots containing trees. In addition, the six trees with sap flux gauges attached had all their pruned leaves collected as separate subsamples, bringing the total number of leaves sampled to over 12000. After counting the number of leaves, each subsample was weighed to determine fresh weight and oven-dried to establish dry weight; the overall mean leaf dry weight for the final pruning was 1.522 g leaf $^{-1}$ (s.e. 0.047, number of subsamples = 21). Mean leaf dry weight at the June 1993 pruning was slightly, but not significantly, higher (1.582 g leaf $^{-1}$, s.e. 0.047, number of subsamples = 7) and the sample size was considerably smaller, with less than 2000 leaves from seven subsamples. The majority of the provenance trees were morphologically indistinguishable from those in the main trial. However, mean leaf dry weight for individual trees varied from < 1 to > 2 g, and some of the provenance trees with values near these extremes exhibited different leaf forms from the main trial. Provenance trees with mean leaf dry weight values falling outside an arbitrary range of ± 1 s.d. around the overall provenance mean (1.658 g leaf $^{-1}$, s.e. 0.071, n = 35) were eliminated from this and all subsequent calculations. When the outlying trees were eliminated, the mean leaf dry weight was 1.517 g leaf $^{-1}$ (s.e. 0.045, n = 23), in close agreement with the value for the February 1994 pruning. Because of the much larger number of leaves sampled in February 1993, 1.522 g leaf $^{-1}$ was used as a standard value in all subsequent calculations.

Specific leaf area (SLA) was determined for both the provenance trees and the trees pruned in February 1994. A root/leaf area meter (Delta-T Devices, Cambridge, UK) was calibrated using graph paper replicas of known area and a similar size and shape to the grevillea leaflets; the values obtained proved to be strongly correlated with the true area (r^2 = 0.998, 4 d.f.) The grevillea leaves were divided into individual leaflets prior to measurement and these were then placed on the meter in groups of three or four. Leaves were randomly selected immediately after removal from the trees, placed in sealed plastic bags and stored in a refrigerator until their area could be measured (within 24 h). The leaves for each tree were then bulked and oven-dried, thereby allowing mean SLA values to be calculated for each tree sampled. On the first observation date (June 1993), only three trees were sampled (3-5 leaves per tree), whereas on the second (February 1994) six trees were sampled (10 leaves per tree); the overall mean SLA values of 56.5 (s.e. 2.48) and 50.15 cm^2 g^{-1} (s.e. 2.68) for the two sampling dates were not significantly

different ($p > 0.28$). Due to the larger sample size and its derivation from the main trial, the mean SLA from the second pruning was used in all subsequent calculations.

The pipe model theory (Waring *et al.*, 1982; Whitehead *et al.*, 1984) has been used previously to relate the conducting area of sapwood to leaf area and a similar approach was adopted here. Several multiple regressions of leaf number against tree dimensions (height, basal diameter and their products and quadratics) were performed for the provenance trees. It was assumed, as with pipe model theory, that these tree dimensions would be more closely correlated with leaf area than leaf number. Leaf numbers were therefore first multiplied by the ratio of the mean leaf dry weight per tree (i.e. for individual trees) to the overall mean leaf dry weight to provide a leaf number corrected for leaf size (i.e. where a tree had smaller, lighter than average leaves, this ratio would be < 1 and calculations based on its leaf number would overestimate the true leaf area unless multiplied by this ratio). As basal diameter (BD, cm) alone did not provide a sufficiently accurate model of leaf number, the following relationship was selected on the basis of goodness of fit:

$$L_n = aH \times BD - bH^2 \qquad \textbf{(Eq.4.8)}$$

where H is height (cm), a = 0.5119 and b = 0.00465 (s.e. 0.0596 and 0.00103 respectively, v.r. 1026, d.f. 2, 22, 81.8% of variation accounted for, s.e. of observations 65.3). This relationship was used to estimate leaf numbers for the period up to the first pruning from the monthly measurements of height and basal diameter. Total leaf numbers were also counted for a subsample of trees at the first pruning and the values obtained were strongly correlated with the leaf numbers predicted by Equation 4.8 (means of 489.6 and 461.7 leaves per tree respectively, r^2 0.93, d.f. 12).

As the relationships between tree height, basal diameter and leaf number are likely to change with age and will certainly be affected by pruning, Equation 4.8 could not be employed over the entire duration of the trial. After the final pruning, full leaf counts were carried out on three randomly selected trees per plot and relationships were established using the same methodology as for Equation 4.8, to permit the estimation of

post-pruning leaf number. All pruned leaves were weighed for every tree row in each plot containing trees and the mean leaf number removed per row was calculated. The value obtained was added to the post-pruning estimates of leaf number to provide values for pre-pruning leaf number, from which the following relationship was derived:

$$L_n = aH + bBD^2 \qquad \textbf{(Eq.4.9)}$$

where a = 2.891 and b = 6.12 (s.e. 0.35 and 1.83 respectively, v.r. 2229.6, d.f. 2, 62, 63.5% of variation accounted for).

The dynamic nature of the relationship between tree dimensions (H and BD) and leaf number over time had to be incorporated into the estimates of the leaf number for the period between the two prunings (6 June 1993 - 23 February 1994). Therefore, rather than using either of the individual equations, a combination equation was used as shown below:

$$L_n = \left\{\frac{(T-t)}{T} \times (1-P_{lr}) \times L_{m1}\right\} + \left\{\frac{t}{T} \times L_{m2}\right\} \qquad \textbf{(Eq.4.10)}$$

where T is the time interval between the pruning dates, t is the number of days after the first pruning, P_{lr} is the proportion of leaves removed and L_{m1} and L_{m2} are the leaf numbers calculated from Equations. 4.8 and 4.9.

Woody biomass

Standing stem biomass (kg tree^{-1} or t ha^{-1}) was calculated from stem volume and density. Total leaf dry weight was calculated from leaf number and overall mean leaf dry weight. Leaf number was estimated using Equation 4.10 and overall mean leaf dry weight was calculated from the leaf area and specific leaf area data using Equation 4.7. The ratio of branch to leaf dry weight was calculated at pruning; the value of this ratio altered with time and a combination model was used to interpolate between the first and final prunings (as in Eq. 4.10). Branch dry weight was calculated from the resulting ratio and the calculated values of leaf dry weight.

4.5 CROP GROWTH ANALYSIS AND HARVESTS

Sampling during the first two cropping seasons (i.e. short rains 1991/2 and long rains 1992) was restricted to end-of-season harvests, and intensive measurements during the season commenced only at the start of the 1992/3 short rains. Growth analyses were undertaken for both sole cowpea (Cg) and cowpea grown with dispersed trees (CTd) at approximately 10 day intervals throughout the growing season. Growth analysis was restricted to these two treatments because of its labour-intensive nature; CTd was chosen because it was expected that tree/crop interactions would be greater than in the line-planted treatments. All other treatments were sampled only at final harvest.

The long rains of 1993 were extremely poor, providing less than 25% of the average seasonal rainfall (Fig. 4.7). The rainfall was both sparse and poorly distributed, with the second rainfall event (> 1 mm) of the season occurring 15 days after the modest first event (11 mm); this resulted in the partial emergence of the maize, which soon wilted irreversibly. The resulting irregular and severely stressed crop was therefore removed and, as there was insufficient additional rainfall to permit resowing, the season had to be abandoned in terms of the assessment of tree/crop interactions.

Final harvest strategy for 1991/2 short rains and 1992 long rains

Cowpea and maize were harvested by row; before measuring fresh weight, the cowpea was separated into pods and haulms, and the maize into stover, cobs and grain. One metre wide guard rows were left on all sides of the plots. Subsamples taken from all plots and oven-dried at 60 ^{0}C for 24 h to determine dry weight.

Routine sampling strategy for 1992/3 short rains

A sample of 36 cowpea plants (12 plants from 3 rows) was taken from one corner of a cell (the 3 x 4 m area with a tree at each corner, cf. Fig. 4.8) in each CTd plot or from an equivalent area in the Cg plots at each harvest. Two plants from each row were quickly separated into leaves, stems and pods and weighed in the field; the total fresh weight of each of the remaining plants was also determined. All plants were separated into leaves, stems and pods before oven-drying at 60 ^{0}C for 24 h.

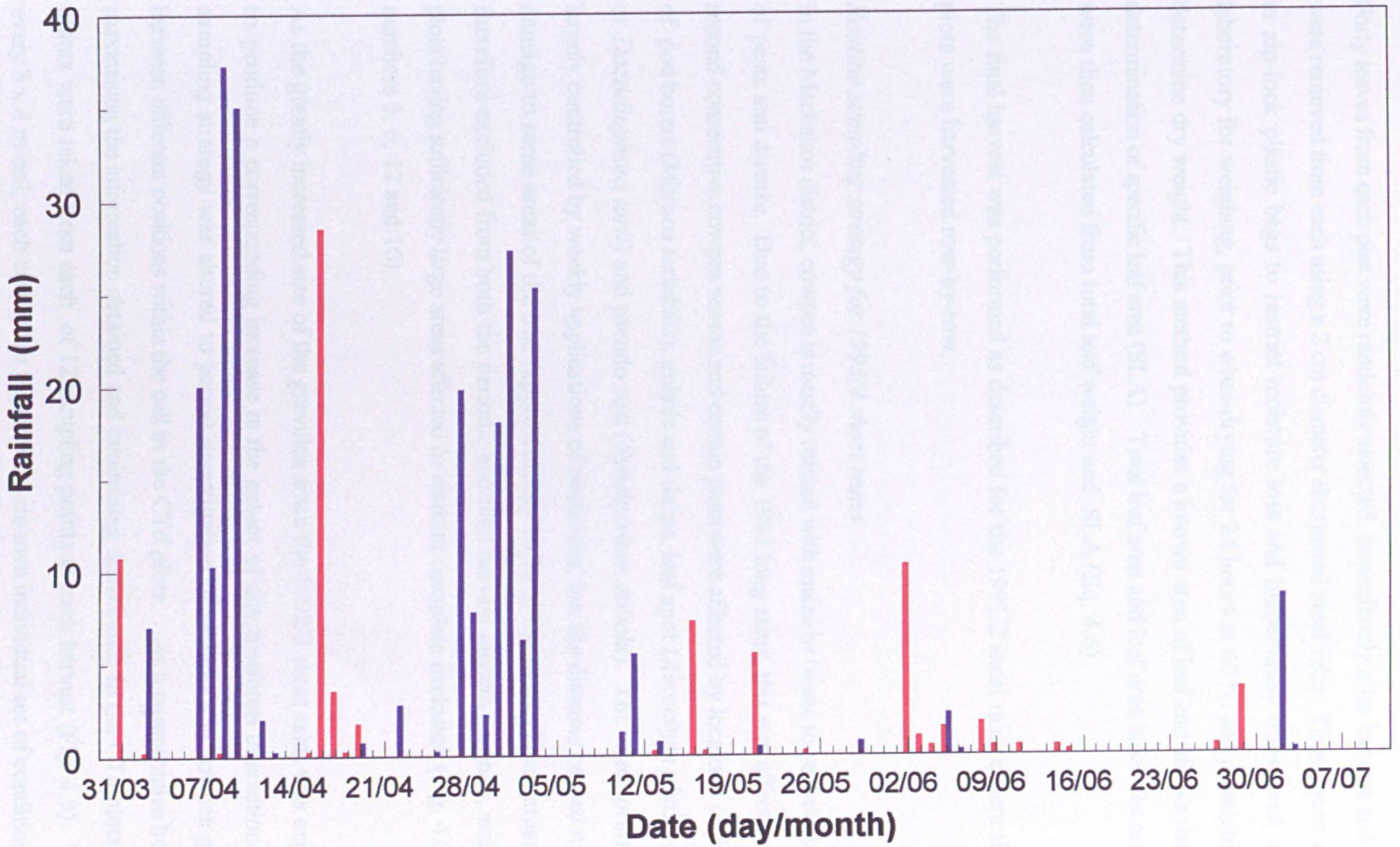


Figure 4.7 Total daily rainfall at ICRAF Machakos Research Station during the long rains of 1992 (blue bars) and 1993 (red bars).

Forty leaves from each plot were randomly selected immediately after harvest and disks were removed from each using a 2 cm diameter sharpened steel tube. These were sealed in zip-lock plastic bags to restrict moisture loss and immediately transferred to the laboratory for weighing, prior to oven-drying for 24 hours at 60 °C and reweighing to determine dry weight. This method provides a known area of leaf and allows the easy determination of specific leaf area (SLA). Total leaf area and leaf area index for cowpea were then calculated from total leaf weight and SLA (Eq. 4.6).

The final harvest was performed as described for the 1991/2 short rains except that all plots were harvested row-by-row.

Routine sampling strategy for 1993/4 short rains

In the Machakos district, cowpea is usually rotated with maize or beans to reduce the risk of pests and disease. Due to the failure of the 1993 long rains, this was effectively the second consecutive cowpea season and certain plots were affected by localised outbreaks of pod borers (*Maruca testulalis*), aphids and thrips, leaf spot (*Ascochyta phaseolorum* or *Dactuliophora tarii*) and pseudo rust (*Synchytrium dolichi*). The insect pests were largely controlled by weekly applications of pesticides, but the diseases caused marked damage to some areas of the trial (approximately 15 % of the area). These areas were therefore excluded from both the periodic and final harvest growth analyses, with four plots having sufficiently large areas affected to warrant complete exclusion (Fig. 4.3, plot numbers 5, 6, 12 and 16).

As the greatly increased size of the grevillea since the 1992/3 short rains was expected to produce a corresponding increase in the extent of any tree/crop interactions, the sampling strategy was altered to permit investigation of variations in cowpea growth between different positions within the cell in the CTd plots. As a compromise between maximising the information obtained and minimising disturbance to the CTd plots, three plants were taken from each of 12 sampling points at each harvest (Fig. 4.9). Within every 3 x 4 m cell, each crop plant experiences its own individual set of conditions, but plants at equivalent positions in other cells experience similar conditions. The right-hand

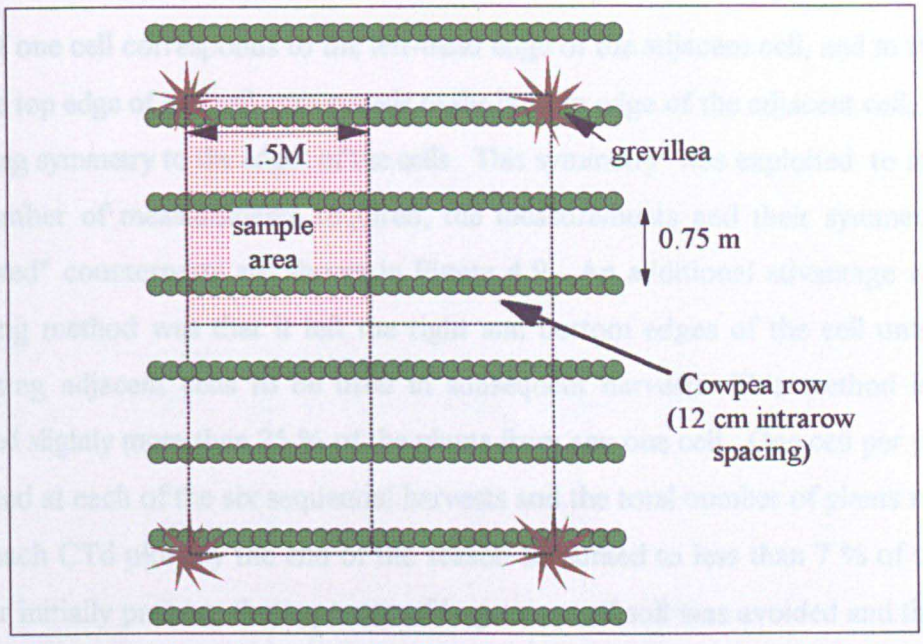


Figure 4.8 Sampling area in the CTd plots for cowpea growth analysis during the 1992/3 short rains. The area removed for growth analysis comprised one quarter of the 3 by 4 m cell with a tree at each corner.

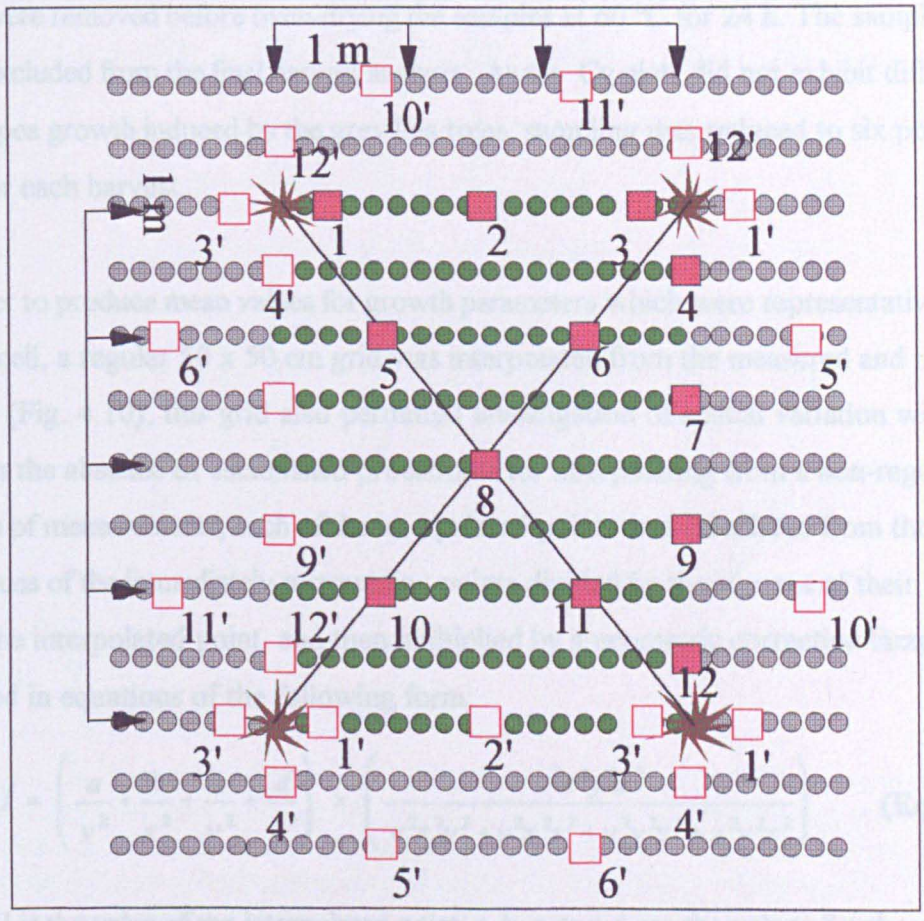


Figure 4.9 Sampling points (■) in the CTd plots during the 1993/4 short rains and the equivalent positions to the sampling points which are on the cell boundary (the 3 x 4 m area with a tree at each corner) or in adjacent cells (□, see text). The circles represent the cowpea positions. An identical sampling pattern was used for growth analysis, light interception and porometry.

edge of one cell corresponds to the left-hand edge of the adjacent cell, and in the same way the top edge of one cell corresponds to the bottom edge of the adjacent cell, thereby providing symmetry to the edges of the cells. This symmetry was exploited to minimise the number of measurements required; the measurements and their symmetrical or "mirrored" counterparts are shown in Figure 4.9. An additional advantage with this sampling method was that it left the right and bottom edges of the cell untouched, permitting adjacent cells to be used in subsequent harvests. This method involved removed slightly more than 25 % of the plants from any one cell. One cell per plot was harvested at each of the six sequential harvests and the total number of plants removed from each CTd plot by the end of the season amounted to less than 7 % of the total number initially present; the exposure of large areas of soil was avoided and the water balance of the plots was therefore probably not substantially altered. The plants removed from each sampling point were separated into leaves, stems and pods, and leaf disks were removed before oven-drying the samples at 60 °C for 24 h. The sampled cells were excluded from the final harvest analysis. As the Cg plots did not exhibit differences in cowpea growth induced by the grevillea trees, sampling was reduced to six points per plot for each harvest.

In order to produce mean values for growth parameters which were representative of the entire cell, a regular 50 x 50 cm grid was interpolated from the measured and mirrored values (Fig. 4.10); this grid also permitted investigation of spatial variation within the cell. In the absence of established procedures for interpolating from a non-regular grid pattern of measurements, each of the interpolated points was calculated from the sum of the values of the immediately surrounding points divided by the squares of their distance from the interpolated point and then multiplied by a geometric correction factor. This resulted in equations of the following form:

$$I = \left(\frac{a}{v^2} + \frac{b}{x^2} + \frac{c}{y^2} + \frac{d}{z^2} \right) \times \left(\frac{v^2x^2y^2z^2}{v^2x^2y^2 + v^2x^2z^2 + v^2y^2z^2 + x^2y^2z^2} \right) \qquad \textbf{(Eq.4.11)}$$

where I is the value of the interpolated point, a, b, c and d are the values for the sampling points immediately surrounding the interpolated point and v, x, y and z are the corresponding distances of the sampling points from the interpolated point.

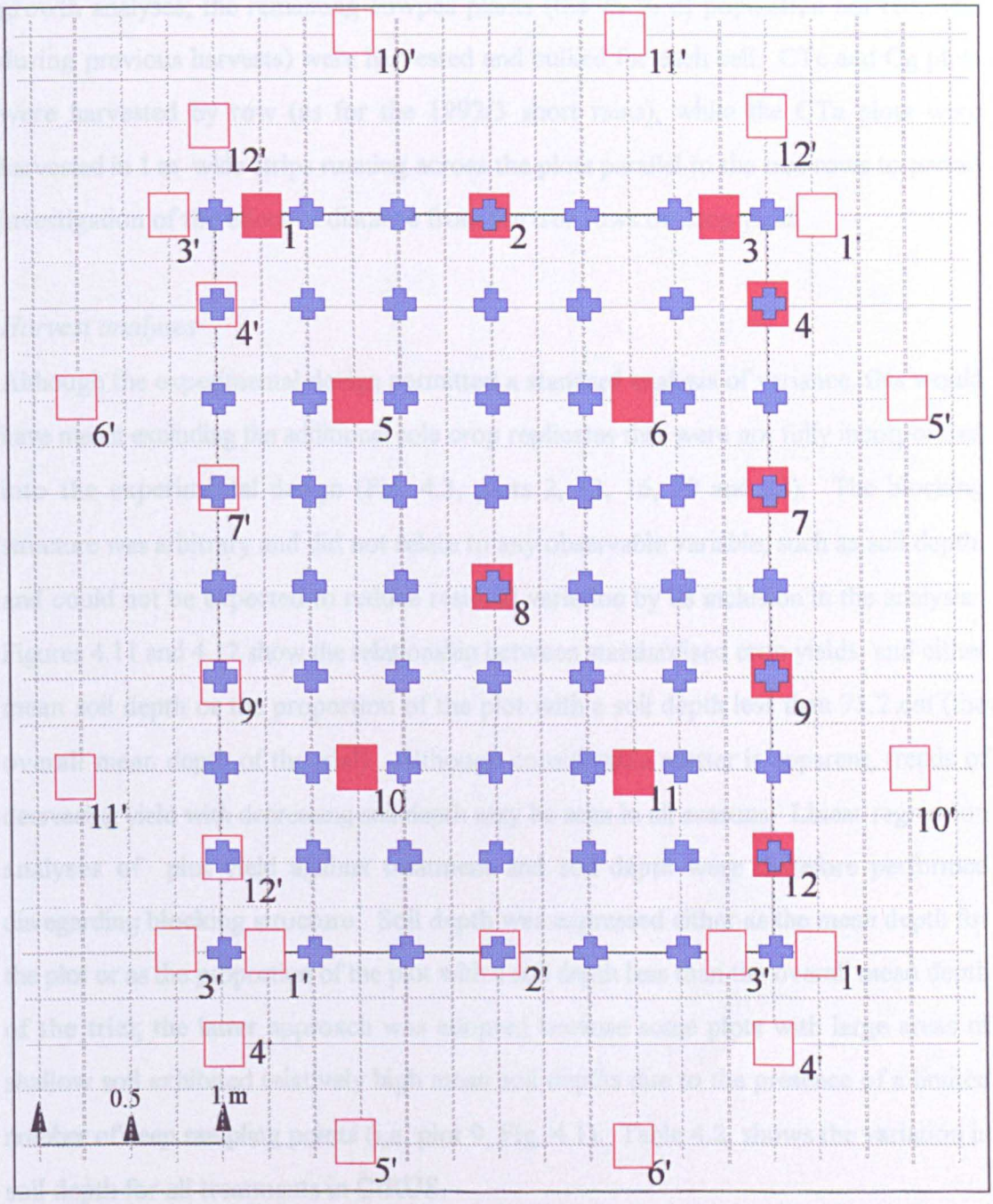


Figure 4.10 The sampling points (■) in the CTd plots during the 1993/4 short rains and the equivalent positions to the sampling points which are on the cell boundary (the 3 x 4 m area with a tree at each corner) or in the adjacent cells (□) (cf. Fig. 4.9). The values measured at the sampling points were assigned to the equivalent positions and the 50 x 50 cm grid values (+) were then interpolated from the values for both the sampled and equivalent positions (see text).

At final harvest, all cells in the CTd plots not sampled previously were sampled for growth analyses; the remaining cowpea plants (the 75 % of population not removed during previous harvests) were harvested and bulked for each cell. CTc and Cg plots were harvested by row (as for the 1992/3 short rains), while the CTa plots were harvested in 1 m wide strips running across the plots parallel to the tree rows to permit investigation of the effect of distance from the tree rows on crop yield.

Harvest analyses

Although the experimental design permitted a standard analysis of variance, this would have meant excluding the additional sole crop replicates that were not fully incorporated into the experimental design (Fig. 4.3, plots 2, 13, 16, 19 and 24). The blocking structure was arbitrary and did not relate to any observable variable, such as soil depth, and could not be expected to reduce residual variation by its inclusion in the analysis. Figures 4.11 and 4.12 show the relationship between standardised crop yields and either mean soil depth or the proportion of the plot with a soil depth less than 71.2 cm (the overall mean depth of the trial). Although considerable scatter is apparent, trends of decreasing yield with decreasing soil depth may be seen in all seasons. Linear regression analyses of plot yield against treatment and soil depth were therefore performed disregarding blocking structure. Soil depth was expressed either as the mean depth for the plot or as the proportion of the plot with a soil depth less than the overall mean depth of the trial; the latter approach was adopted because some plots with large areas of shallow soil exhibited relatively high mean soil depths due to the presence of a limited number of deep sampling points (i.e. plot 9, Fig. 4.1). Table 4.2 shows the variation in soil depth for all treatments in CIRUS.

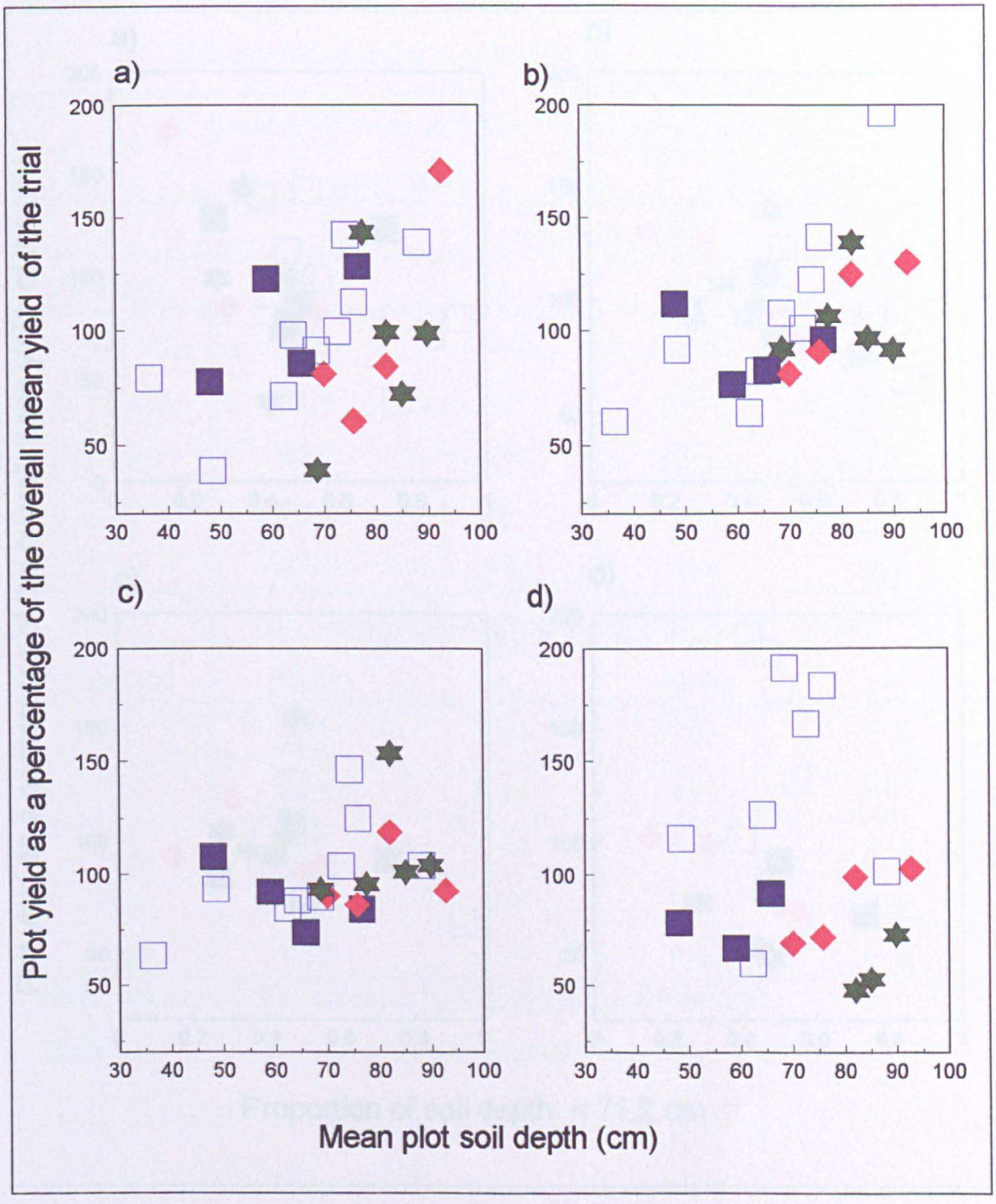


Figure 4.11 Relationship between individual plot yields expressed as a percentage of the overall mean yield of the trial and mean plot soil depths for (a) short rains 1991/2, (b) long rains 1992, (c) short rains 1992/3 and (d) short rains 1993/4.□, ■, ✶ and ◆ represent treatments Cg, CTc, CTd and CTa respectively. NB. One CTd plot was converted to a Cg plot after the short rains 1992/3 and data for certain plots were omitted during the final season because of disease (see text).

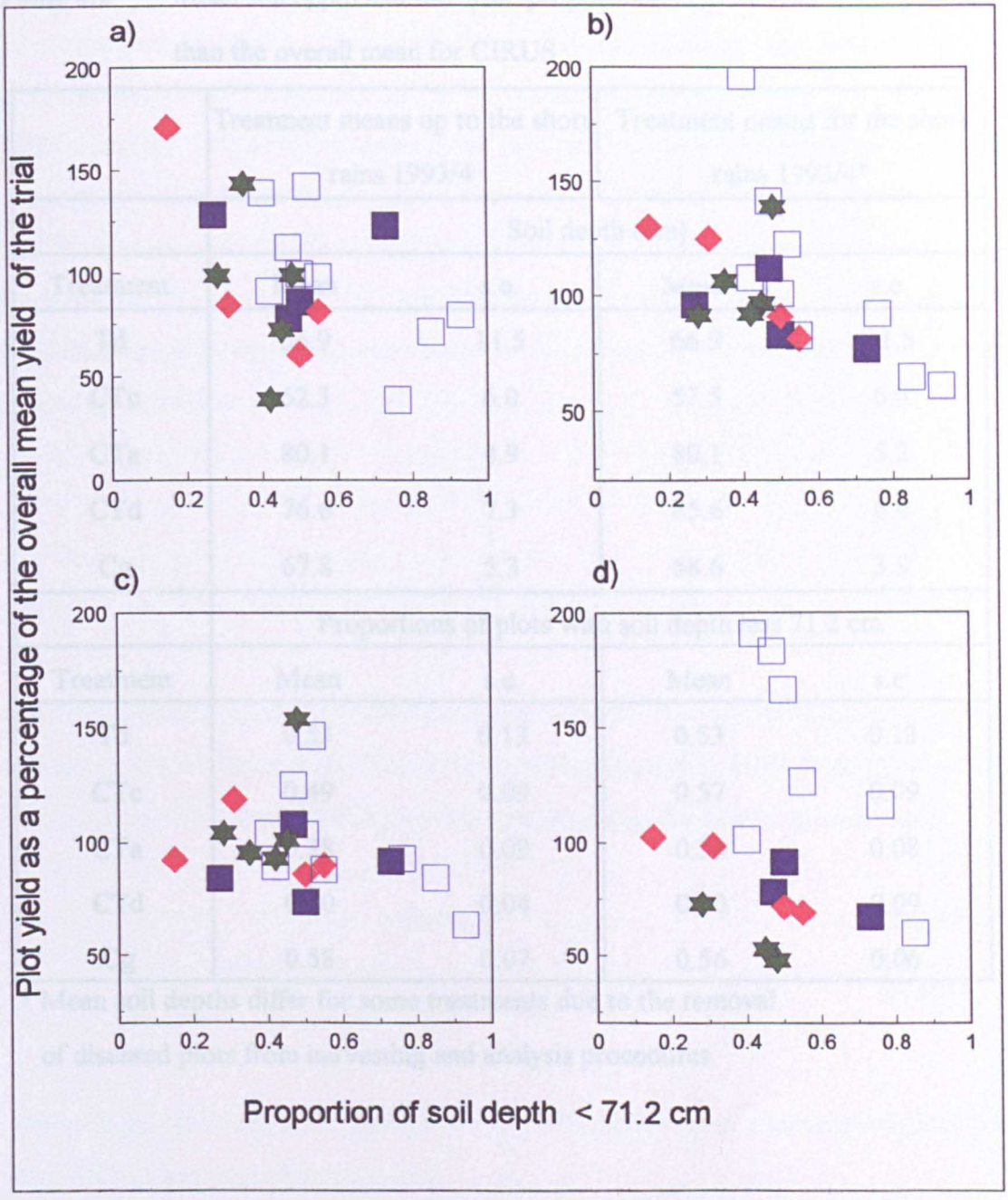


Figure 4.12 Relationship between individual plot yields expressed as a percentage of the overall mean yield of the trial and the proportion of the plot with a soil depth less than the overall mean soil depth for the trial (71.2 cm) for (a) short rains 1991/2, (b) long rains 1992, (c) short rains 1992/3 and (d) short rains 1993/4. □, ■, ✶ and ◆ represent treatments Cg, CTc, CTd and CTa respectively. NB. One CTd plot was converted to a Cg plot after the short rains 1992/3 and data for certain plots were omitted during the final season because of disease (see text).

Table 4.2 Mean soil depth and the mean proportions of plots with soil depths less than the overall mean for CIRUS

	Treatment means up to the short rains 1993/4		Treatment means for the short rains 1993/4*	
	Soil depth (cm)			
Treatment	Mean	s.e.	Mean	s.e.
Td	66.9	11.5	66.9	11.5
CTc	62.3	6.0	57.5	6.0
CTa	80.1	4.9	80.1	5.2
CTd	76.6	7.3	85.6	6.0
Cg	67.8	5.3	68.6	3.9
	Proportions of plots with soil depth less 71.2 cm			
Treatment	Mean	s.e.	Mean	s.e.
Td	0.53	0.13	0.53	0.13
CTc	0.49	0.09	0.57	0.09
CTa	0.38	0.09	0.38	0.08
CTd	0.40	0.04	0.40	0.09
Cg	0.58	0.07	0.56	0.06

* Mean soil depths differ for some treatments due to the removal of diseased plots from harvesting and analysis procedures.

4.6 LIGHT INTERCEPTION BY TREES AND CROPS

Photosynthetically active radiation (PAR) was measured at mid-day using a Sunfleck Ceptometer (Delta-T Devices, UK) at 1-2 week intervals (cf. Section 2.3) during the 1992/3 and the 1993/4 short rains. Total incident PAR and PAR transmission by the canopies of both grevillea and cowpea were measured on each occasion. Incident PAR and PAR transmission by the grevillea trees were also measured on several occasions between the two short rainy seasons. Fractional interception of PAR by the grevillea (Tf_p) and the sole cowpea (Cf_p) was calculated for each measurement location using the following equations:

$$Tf_p = \frac{T_t}{I_p} \qquad \textbf{(Eq.4.12)}$$

$$Cf_p = \frac{C_t}{I_p} \qquad \textbf{(Eq.4.13)}$$

where T_t and C_t represent PAR transmission by the tree and crop canopies and I_p represents total incident PAR. The fraction of total incoming PAR intercepted by the intercropped cowpea plants (Cf_{pi}) was calculated using the following equations:

$$Cf_i = \frac{C_t}{T_t} \qquad \textbf{(Eq.4.14)}$$

$$Cf_{pi} = Cf_i \times (1 - Tf_p) \qquad \textbf{(Eq.4.15)}$$

where Cf_i denotes fractional interception of PAR incident upon the cowpea plants (i.e. the PAR not intercepted by the trees).

Short rains 1992/3

Figure 4.13 shows the locations of the ceptometer measurements of PAR interception by the grevillea in the CTd and Td treatments; three trees per plot were chosen at random for examination. The ceptometer probe is 80 cm long and well suited to providing integrated measurements of PAR on this scale. In the dispersed tree treatments, there was one tree per 12 m^2 of land area, and this area was sub-divided for the purpose of

measurement and calculation of Tf_p. The measurement locations closest to the trees (1t, 3t, 5t and 7t) and those furthest from the trees (2t, 4t, 6t and 8t) spanned sampling areas of 2.01 m^2 and 6.03 m^2 respectively; mean Tf_p for each tree was then calculated as:

$$\overline{Tf_p} = \frac{(Tf_{p1} + Tf_{p3} + Tf_{p5} + Tf_{p7})x2.01 + (Tf_{p2} + Tf_{p4} + Tf_{p6} + Tf_{p8})x6.03}{48} \quad \textbf{(Eq.4.15)}$$

where Tf_{p1} to Tf_{p8} represent the fractional interception of PAR measured at locations 1t to 8t ; Tf_p beyond the outermost locations was assumed to be negligible at this stage of tree growth. For cowpea plants in the CTd plots, ceptometer measurements of PAR were made above and below the crop at two positions in each of three crop rows covering one quarter of the cell (the 3 by 4 m rectangle with a tree at each corner), with the same number and arrangement adopted for sole cowpea. Tree and crop measurements were made in four replicates of CTd, Td and Cg.

Tf_p might be expected to increase throughout the season as leaf area increased. Its initial value and rate of increase might also be expected to be approximately proportional to the initial leaf area. However, the variability of the Tf_p values recorded for individual treatments tended to mask this trend (Fig. 4.14). In order to interpolate Tf_p values between consecutive measurement dates, multiple regression analysis of Tf_p against days after emergence[1] of the cowpea (D_e) and treatment was performed, resulting in the following equation:

$$Tf_p = k(a + bD_e) \quad \textbf{(Eq. 4.16)}$$

where a = 2.116, b = 0.0474 and k = 2.488 (s.e. 0.746, 0.0141 and 0.367 respectively, v.r. 127.7, d.f. 3, 9, 86.4% of variation accounted for). Tf_p was expressed as a percentage in the derivation of Equation 4.16. k is a proportionality constant derived from the regression analysis (to account for the proportional difference in initial leaf area

[1]Days after emergence (DAE) was sometimes used in place of days after sowing (DAS) during analysis. For this study DAE is equivalent to DAS minus 5 days.

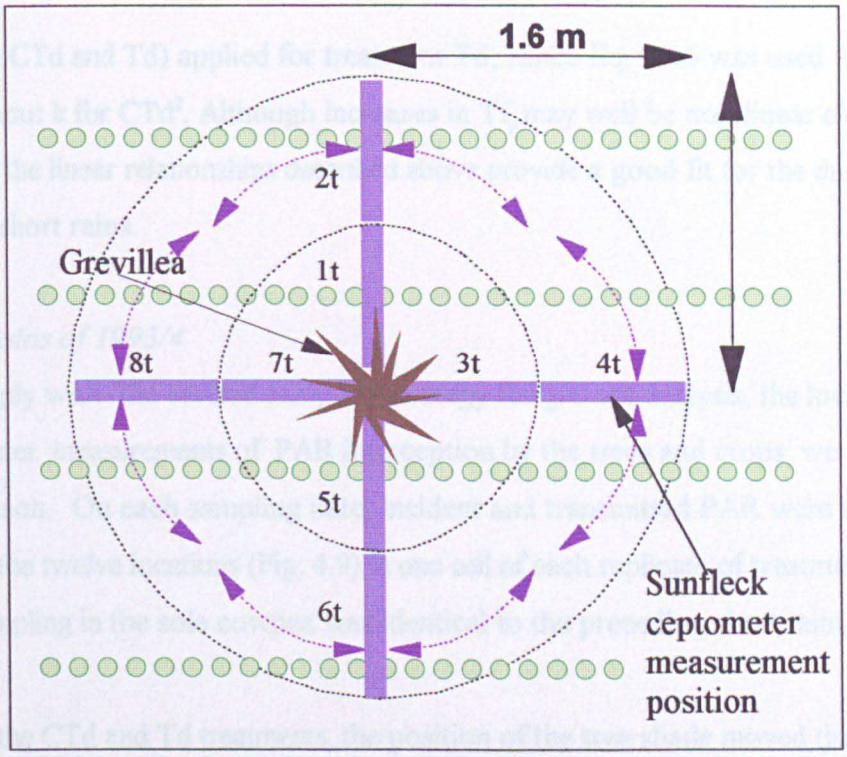


Figure 4.13 Sunfleck ceptometer sampling positions (numbered 1t to 8t) for measuring photosynthetically active radiation (PAR) interception by grevillea trees in the CTd and Td treatments during the 1992/3 short rains. The purple bars represent the positions of the 80 cm long ceptometer probe. Total incident PAR and transmitted PAR below the trees were recorded at each sampling location and the "cross-shaped" sampling grid was randomly orientated. The concentric circles show the areas represented by sampling locations 1t, 3t, 5t and 7t (inner circle) and by 2t, 4t, 6t and 8t (between inner and outer rings). ● shows the positions of the cowpea rows in the CTd plots.

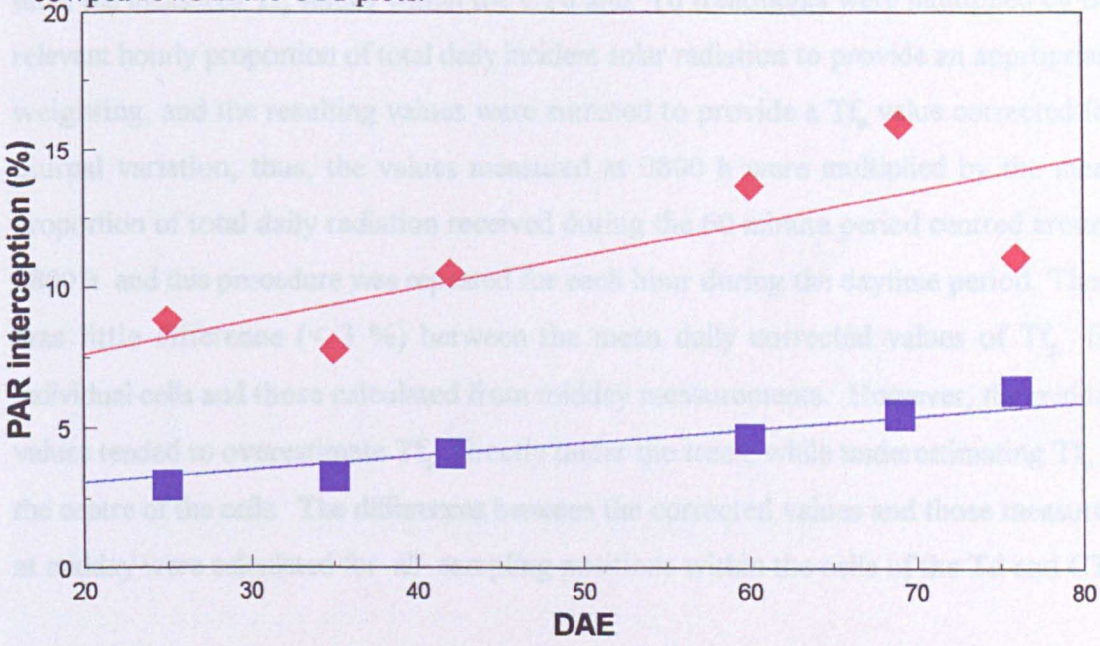


Figure 4.14 Percentage of photosynthetically active radiation (PAR) intercepted by grevillea (Tfp) in the CTd (■) and Td (◆) treatments during the 1992/3 short rains and regression lines of best fit (see text for equations). Days after emergence (DAE) of cowpea were used for the analysis in this instance.

between CTd and Td) applied for treatment Td; hence Eq. 4.16 was used with k for Td and without k for CTd[2]. Although increases in Tf_p may well be non-linear over extended periods, the linear relationships described above provide a good fit for the duration of the 1992/3 short rains.

Short rains of 1993/4

To comply with the revised sampling strategy for growth analysis, the locations of the ceptometer measurements of PAR interception by the trees and crops were altered for this season. On each sampling date, incident and transmitted PAR were measured at each of the twelve locations (Fig. 4.9) in one cell of each replicate of treatments CTd and Td. Sampling in the sole cowpea was identical to the preceding short rains experiment.

In both the CTd and Td treatments, the position of the tree shade moved throughout the day and the measured Tf_p values at specific sampling positions varied considerably. In order to establish an integrated daily value for Tf_p for all sampling points (Figs. 4.9 & 4.10) in the cells, serial PAR measurements were made from one hour after dawn until one hour before dusk. Figure 4.15 shows the diurnal variation in the hourly proportion of total daily incident solar radiation during the 1993/4 short rains. For each sampling time, the measured Tf_p values within the CTd and Td treatments were multiplied by the relevant hourly proportion of total daily incident solar radiation to provide an appropriate weighting, and the resulting values were summed to provide a Tf_p value corrected for diurnal variation; thus, the values measured at 0800 h were multiplied by the mean proportion of total daily radiation received during the 60 minute period centred around 0800 h and this procedure was repeated for each hour during the daytime period. There was little difference (< 3 %) between the mean daily corrected values of Tf_p for individual cells and those calculated from midday measurements. However, the midday values tended to overestimate Tf_p directly under the trees, while underestimating Tf_p in the centre of the cells. The differences between the corrected values and those measured at midday were calculated for all sampling positions within the cells of the Td and CTd

[2]See Genstat 5 Reference Manual (1988), Chapter 8, for an explanation of multiple regression analysis with proportionality constants.

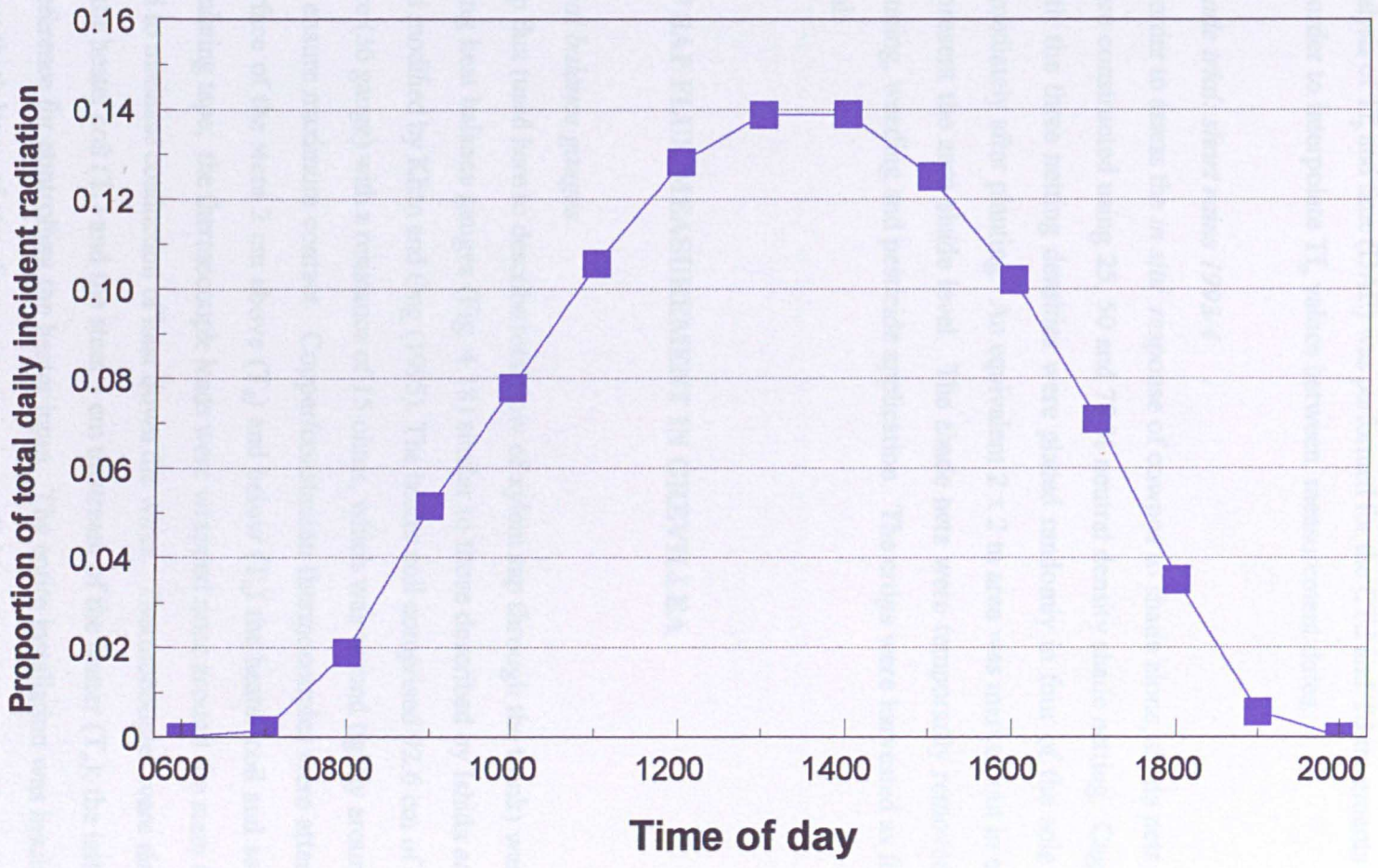


Figure 4.15 Diurnal variation in the hourly proportion of total daily incident solar radiation at Machakos during the short rains of 1993/4. Data represent the seasonal mean.

treatments and used to correct the Tf_p values obtained from midday measurements for the remainder of the season. As for the preceding short rains, multiple regression analysis of Tf_p and time (DAE) was performed for the CTd and Td treatments (Fig. 4.16) in order to interpolate Tf_p values between measurement dates.

Shade trial: short rains 1993/4

In order to assess the *in situ* response of cowpea to shade alone, shade nets (Fig. 4.17) were constructed using 25, 50 and 75 % neutral density shade netting. Cages covered with the three netting densities were placed randomly in four of the sole crop plots immediately after planting. An equivalent 2 x 2 m area was marked out in each plot to represent the zero shade level. The shade nets were temporarily removed to permit thinning, weeding and pesticide application. The crops were harvested as for the main trial.

4.7 SAP FLUX MEASUREMENT IN GREVILLEA

Heat balance gauges

Sap flux (used here to describe total flow of xylem sap through the trunk) was measured using heat balance gauges (Fig. 4.18) similar to those described by Ishida *et al.* (1991) and modified by Khan and Ong (1995). The heater coil comprised 92.6 cm of constantan wire (36 gauge) with a resistance of 15 ohms, which was wound tightly around the stem to ensure maximum contact. Copper/constantan thermocouples were attached to the surface of the stem 2 cm above (T_d) and below (T_u) the heater coil and secured with insulating tape; the thermocouple leads were wrapped once around the stem for support and to minimise conduction of heat down the wires. Thermocouples were also attached to the heater coil (T_h) and the stem 4 cm upstream of the heater (T_o); the latter acted as a reference for controlling the heater input. The entire installation was insulated with a 5 cm thick layer of styrofoam to minimise radial heat exchange and interference from fluctuations in ambient temperature. This insulation and a 5-10 cm length of stem on either side of the insulation were covered with aluminium foil to minimise solar heating and other sources of radiant energy such as warm soil; the foil was sealed around the

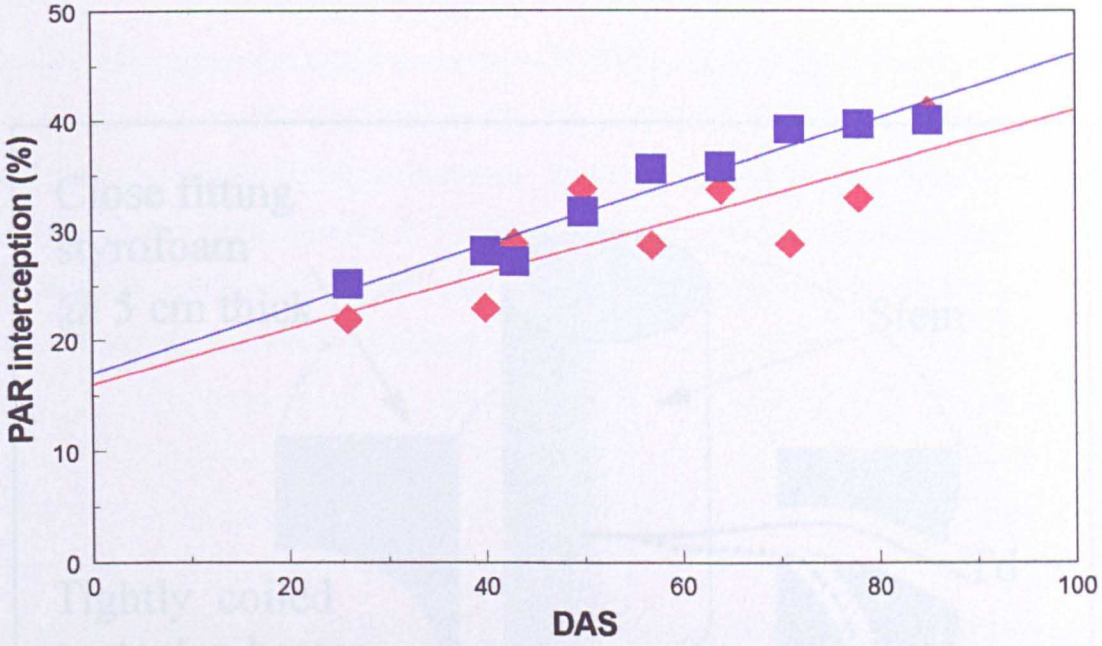


Figure 4.16 Timecourses of percentage interception of photosynthetically active radiation (PAR) by grevillea in the CTd (■) and Td (◆) treatments during the 1993/4 short rains. The linear regressions for Td and CTd respectively were $y = 0.25x + 16$, ($r^2 = 0.67$, s.e of parameters 0.067 and 4.0) and $y = 0.29x + 17$, ($r^2 = 0.94$, s.e of parameters 0.027 and 1.6 for CTd).

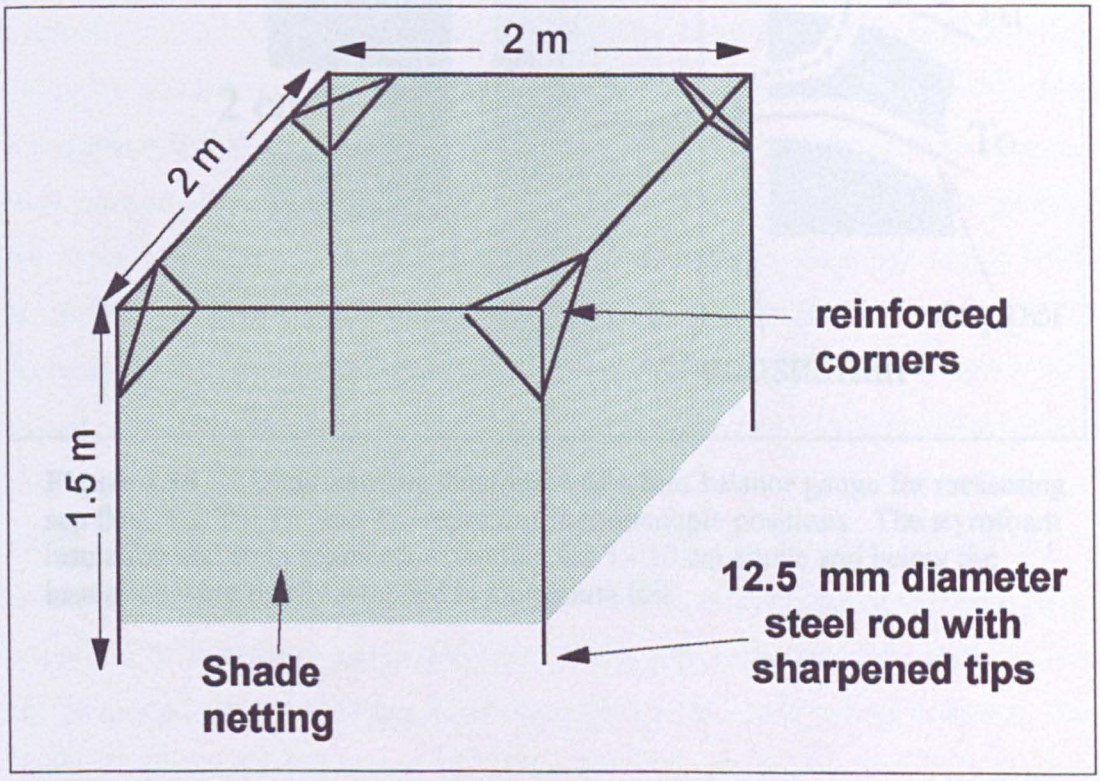


Figure 4.17 Portable shade nets used in the sole cowpea treatments in CIRUS during the 1993/4 short rains.

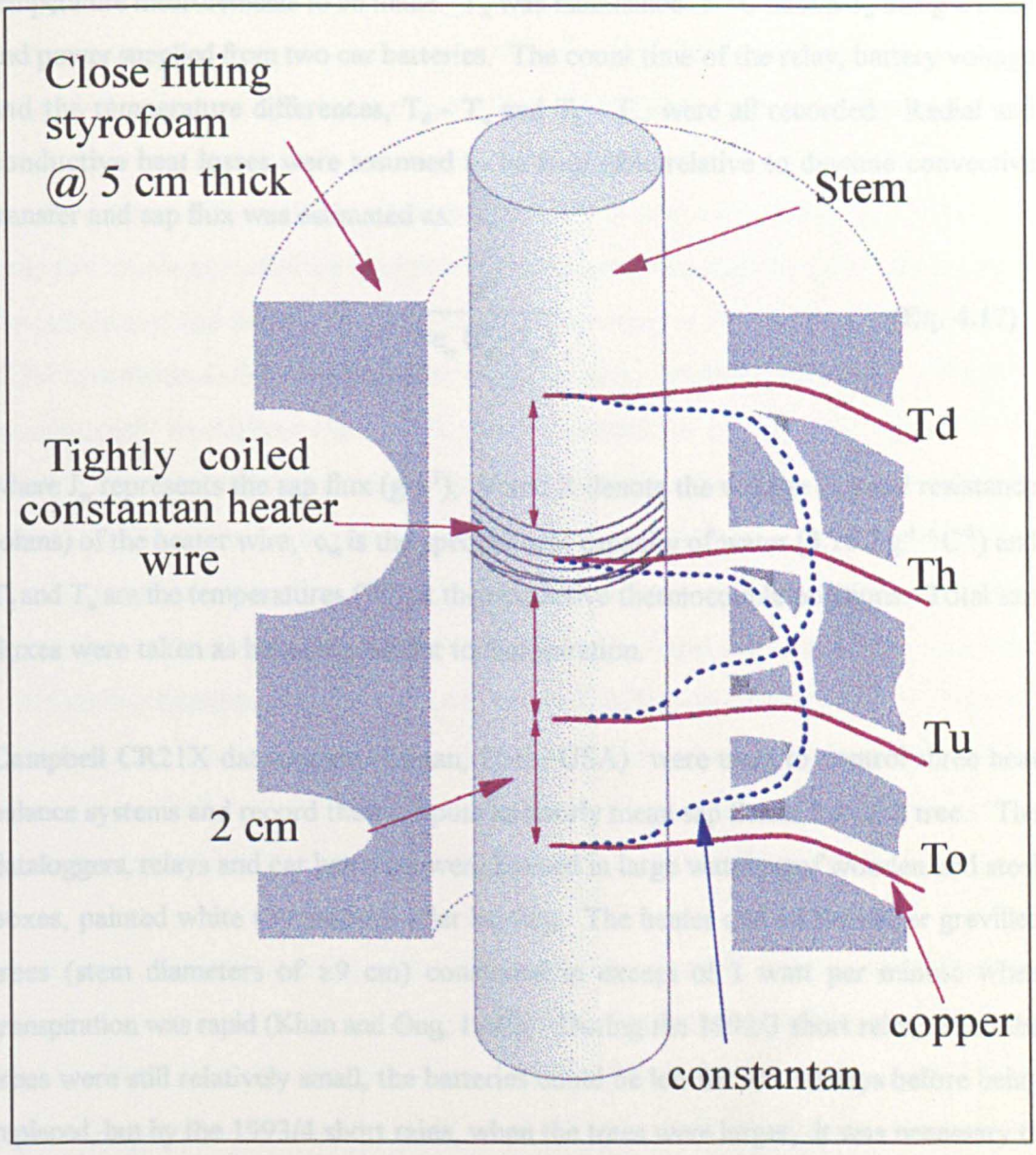


Figure 4.18 Diagrammatic illustration of a heat balance gauge for measuring sap flux. Td, Tu ,Th and To represent thermocouple positions. The styrofoam insulation and stem segments extending for 5 - 10 cm above and below the insulation were tightly wrapped in aluminium foil.

stem using insulation tape.

The thermocouples were linked as two pairs, T_u to T_d and T_h to T_o, to enable differential temperature measurements to be made. T_h was maintained 5 °C above T_o using a relay and power supplied from two car batteries. The count time of the relay, battery voltage and the temperature differences, T_d - T_u and T_h - T_o, were all recorded. Radial and conductive heat losses were assumed to be negligible relative to daytime convective transfer and sap flux was estimated as:

$$J_w = \frac{V^2}{Rc_w(T_d - T_u)} \qquad \textbf{(Eq. 4.17)}$$

where J_w represents the sap flux (g s^{-1}), V and R denote the voltage (V) and resistance (ohms) of the heater wire, c_w is the specific heat capacity of water (4.18 J g^{-1} $°C^{-1}$) and T_d and T_u are the temperatures (°C) at the respective thermocouple positions. Total sap fluxes were taken as being equivalent to transpiration.

Campbell CR21X dataloggers (Logan, Utah, USA) were used to control three heat balance systems and record their outputs as hourly mean sap fluxes for each tree. The dataloggers, relays and car batteries were housed in large waterproof wooden and steel boxes, painted white to minimise solar heating. The heater coil on the larger grevillea trees (stem diameters of ≥9 cm) consumed in excess of 1 watt per minute when transpiration was rapid (Khan and Ong, 1995). During the 1992/3 short rains, when the trees were still relatively small, the batteries could be left for 7 - 10 days before being replaced, but by the 1993/4 short rains, when the trees were larger, it was necessary to check the heater batteries daily and change them at 2-4 d intervals. The rapid rate of battery discharge lead to occasional interruptions in measurements when batteries discharged faster than anticipated. The 70 or 90 ampere hour batteries used to power the heater coils were not primarily designed for deep discharge cycles created by several days of use prior to recharging, and repeated use lowered battery efficiency and shortened their useful life.

Sampling

Gauges were attached to the stems 50 - 150 cm above the ground depending on the height of the trees, and were sited at breast height (130 cm) wherever possible. The gauges were moved to new trees at 7 - 10 d intervals to prevent damage to the cambium and phloem caused by the heater wires cutting into the rapidly expanding stems. Measurements commenced at the start of the 1992/3 short rains. Six dataloggers and 18 gauges were used initially but this was found to be extremely labour-intensive, both during routine daily monitoring and especially when relocating the gauges. Therefore only two dataloggers and six gauges were employed subsequently (after one month of measurements) and sap flow was monitored in three trees in one plot each of the Td and CTd treatments during the remainder of this season. Measurements were carried out continuously throughout the 1992/3 short rains and for the first four months of the ensuing dry season. They were then discontinued at the end of June 1993 to allow a full overhaul of batteries and equipment and recommenced in October 1993, shortly before the 1993/4 short rains. Due to competing demands for loggers and gauges within this and other trials during this season, two dataloggers and six gauges were used and continuous measurements were made over periods of two to three weeks, with intervals of the same duration between consecutive measurement periods within specific treatments. Daily values for the intervening days between consecutive measurement periods were interpolated from the solar radiation data (see Chapter 7.2).

During and after heavy rainfall, water originating from stem flow or the direct impact of rain occasionally penetrated into the gauges. However, as the rainfall occurs mainly at night in Machakos, this did not present a major difficulty since gauges affected in this way dried out by mid-morning. Any missing hourly sap flux values for grevillea were interpolated using values from the unaffected gauges (as for the excavation trees, cf. Section 7.3).

Calibration of the heat balance gauges

This design of heat balance gauge has previously been calibrated for cereal plants, which can readily be grown in pots and whose transpiration can be measured gravimetrically (Khan, pers. comm.). These calibrations demonstrated that the estimates of sap flux were

accurate to within ±10% (Khan, pers. comm.). Khan and Ong (1995) divided the corresponding calibration for grevillea into two stages. The first stage involved a straightforward calibration using a potted grevillea sapling placed on an electronic balance accurate to 1 g. Gravimetric water loss and sap flux were recorded at 30 min intervals. Measured sap flux during the daytime period agreed closely with the gravimetric values ($r^2 = 0.99$, n = 13), but total daily water use was overestimated by 17 %. However, if the night time sap flux was assumed to be zero to compensate for the increased importance of radial and conductive heat losses when sap flux is low, a slight underestimation of total water use of 7 % was obtained, well within the ±10 % accuracy described previously (Baker and van Bavel, 1987; Ishida *et al.*, 1991; Valacogne and Naser, 1993).

The second stage of calibration was carried out using field-grown grevillea trees. The stem diameter of the potted grevillea used by Khan and Ong (1995) was only 20.4 mm, with a maximum corrected sap flux of 80 g h^{-1}. The field-grown grevillea trees examined in the present study had stem diameters four or five times larger, with maximum measured sap fluxes exceeding 2000 g h^{-1}. Due to the logistical difficulties of growing large trees in containers, especially with deep-rooted trees such as grevillea, and in obtaining accurate measurements of weight loss from such systems, Khan and Ong (1995) devised an alternative method for calibrating heat balance gauges for large stems. Trees were selected with larger stems (up to 89 mm diameter) and pruned to leave a single small terminal branch of similar diameter to the stem of the potted tree previously calibrated, and sap flux was then measured for both the stem and branch; the values obtained should be near identical under steady-state conditions. When the sap fluxes were corrected for radial and conductive losses and ambient temperature changes, close agreement was obtained between the branch and stem sap flux measurements (within -6 to +7 %). However, when uncorrected, sap fluxes for the stem were 10 - 45 % greater than those for the branch. The relationship between the ratio of corrected to uncorrected sap flux and stem diameter is shown in Figure 4.19. The ratio was close to 1 until stem diameter exceeded 32 mm, beyond which the values increased almost linearly with increasing stem diameter in a relationship described by:

$$R_c = aD_s + b \qquad \textbf{(Eq.4.18)}$$

where D_s is the stem diameter (mm), a is 0.0102 (s.e. 0.0007), R_c is the ratio of corrected to uncorrected sap flux and b is 0.696 (s.e. 0.047), with an r^2 value of 0.99 (n = 4). This equation was used to correct for overestimation of sap flux in grevillea trees with stem diameters exceeding 32 mm. The erroneous values for large stems may have been caused by incomplete thermal mixing within the sap (as decribed by Sabatti *et al.*, 1993).

When the grevillea trees were sufficiently large (i.e. >2.0 - 2.5 m tall), heat balances were attached approximately at breast height and diameter at breast height (DBH) was taken as equivalent to D_s. Figure 4.20 shows the relationship between basal diameter (BD, cm) and DBH (cm), which can be described by the following equation:

$$DBH = axBD - b \qquad \textbf{(Eq.4.19)}$$

where a is 0.754 and b is 1.257 (s.e.s 0.013 and 0.121; $r^2 = 0.92$, n = 312). BD was measured routinely for all trees used for heat balance measurements, whereas DBH was only measured periodically. Where not measured, DBH was calculated using Eq. 4.19 prior to inclusion in Eq. 4.18 for calculation of R_c.

4.8 EXCAVATION OF THE ROOTING SYSTEM OF GREVILLEA

To quantify the degree of below-ground complementarity in water use between grevillea and cowpea, transpiration by the trees was measured using heat balance gauges attached to the stems of young grevillea trees (10-18 month old), both before and after excavating the crop rooting zone (upper 60 cm of soil) from around the stem base. The crop rooting zone was removed to establish the capacity of the grevillea to extract water from beneath this zone.

Excavation

The excavations were carried out in an area adjacent to the main CIRUS trial which had

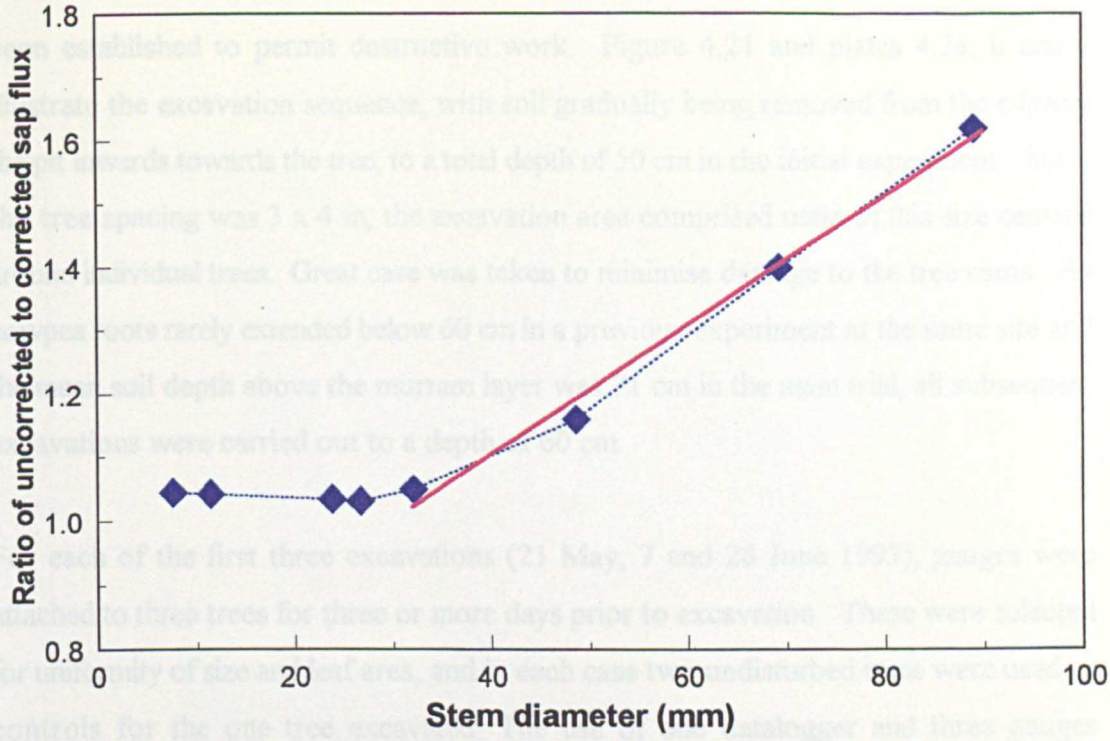


Figure 4.19 The relationship between the ratio of uncorrected to corrected sap flux and stem diameter in grevillea trees (calculated from data provided by A A H Khan, pers. comm.).

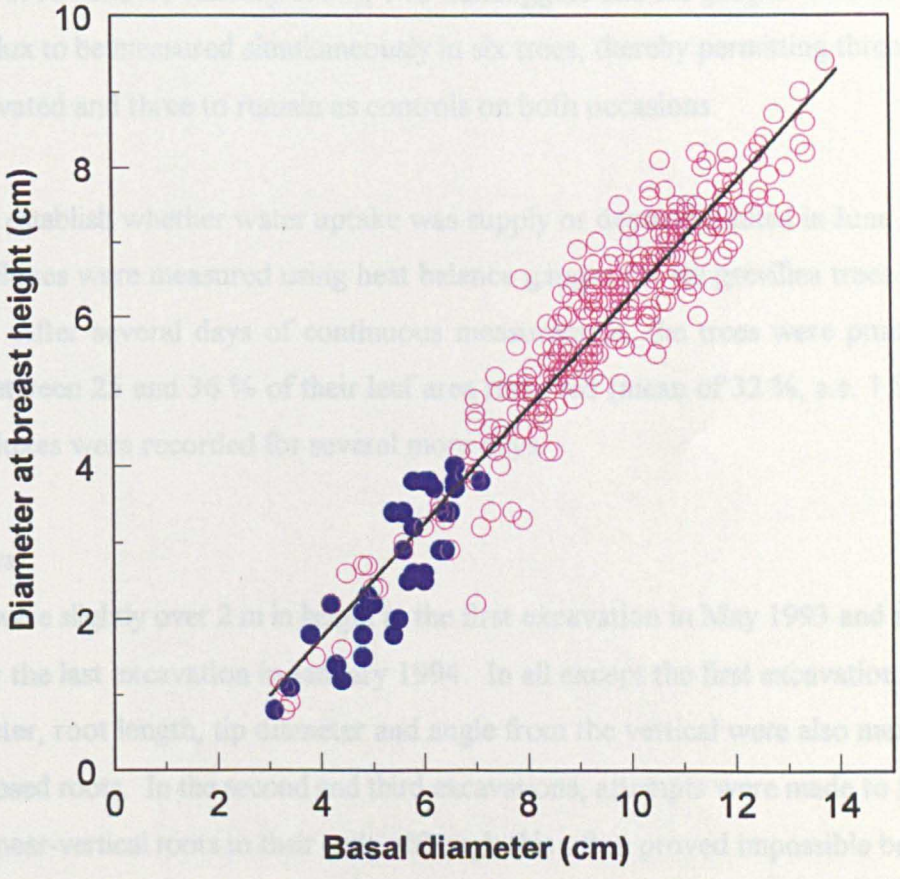


Figure 4.20 The relationship between basal diameter (BD) and diameter at breast height (DBH) in 20 (●) and 30 (O) month old grevillea trees.

been established to permit destructive work. Figure 4.21 and plates 4.2a, b and c illustrate the excavation sequence, with soil gradually being removed from the edge of the pit inwards towards the tree, to a total depth of 50 cm in the initial experiment. Since the tree spacing was 3 x 4 m, the excavation area comprised units of this size centred around individual trees. Great care was taken to minimise damage to the tree roots. As cowpea roots rarely extended below 60 cm in a previous experiment at the same site and the mean soil depth above the murram layer was 71 cm in the main trial, all subsequent excavations were carried out to a depth of 60 cm.

For each of the first three excavations (21 May, 7 and 28 June 1993), gauges were attached to three trees for three or more days prior to excavation. These were selected for uniformity of size and leaf area, and in each case two undisturbed trees were used as controls for the one tree excavated. The use of one datalogger and three gauges permitted only one tree to be excavated at any one time if there was to be more than one control. Thus when this procedure was repeated during the 1993/4 short rains (16 December 1993 and 21 January 1994), two dataloggers and six gauges were used to allow sap flux to be measured simultaneously in six trees, thereby permitting three trees to be excavated and three to remain as controls on both occasions.

In order to establish whether water uptake was supply or demand-limited in June 1993, stem sap fluxes were measured using heat balance gauges for six grevillea trees in the main trial. After several days of continuous measurement, the trees were pruned to remove between 25 and 36 % of their leaf area removed (mean of 32 %, s.e. 1.9) and their sap fluxes were recorded for several more days.

Allometrics

The trees were slightly over 2 m in height at the first excavation in May 1993 and almost 4 m tall by the last excavation in January 1994. In all except the first excavation, basal root diameter, root length, tip diameter and angle from the vertical were also measured for all exposed roots. In the second and third excavations, attempts were made to follow the larger near-vertical roots to their ends, although this often proved impossible because the roots penetrated to unknown depths into the murram layer and underlying friable

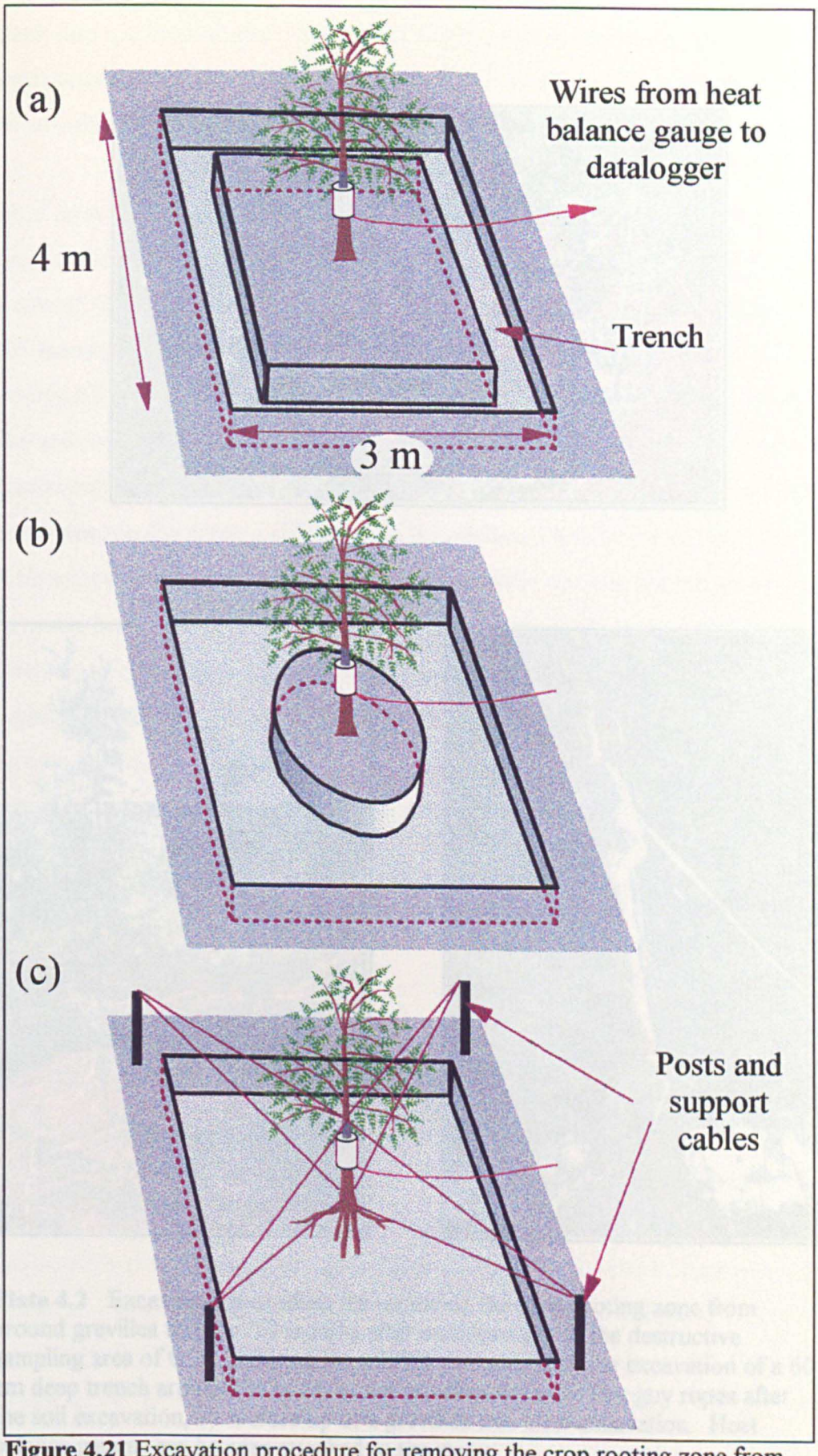
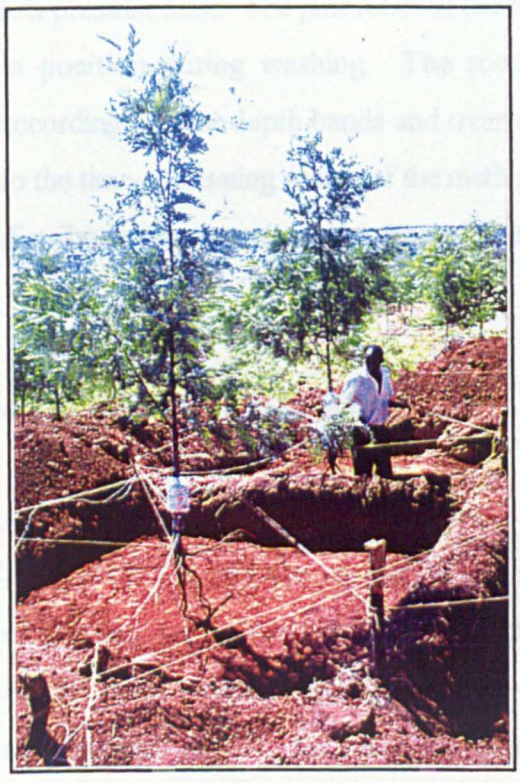


Figure 4.21 Excavation procedure for removing the crop rooting zone from around individual grevillea trees.

a)

b)



c)

Plate 4.2 Excavation procedure for removing the crop rooting zone from around grevillea trees, c. 19 months after establishment in the destructive sampling area of CIRUS during the 1993/4 short rains; a) the excavation of a 60 cm deep trench around the trees, b) the grevillea supported by guy ropes after the soil excavation, c) a close up of a grevillea tree after excavation. Heat balance gauges can be seen attached to the stems.

bedrock through small cracks. Where root length could not be measured directly, this was estimated on the assumption that the roots were conical. This approach may have led to an underestimation of the true root lengths due to their slightly paraboloid shape.

Cowpea roots

During the short rains of 1993/4, the rooting profile for cowpea was examined at 60 days after sowing (DAS; c. 20 d after and 20 d before the excavations on 16 December 1993 and 21 January 1994 respectively) using an open trench approach. A 100 x 60 cm board supporting a 5 x 5 cm grid of 10 cm long pins projecting from its surface was driven into vertical soil profile exposed by digging a trench perpendicular to the cowpea rows. This was sufficiently wide to allow a hydraulic jack to be placed against the opposing face to force the pins into the exposed soil profile. The pin board was then excavated complete with its soil profile and soaked overnight, before gently washing the soil away using a low pressure hose. The pins retained the soil profile during excavation and held the roots in position during washing. The roots were then removed from the grid, bulked according to 5 cm depth bands and oven-dried at 60 °C for 24 h before weighing. Due to the time-consuming nature of the method, a single profile was examined to assess root distribution in cowpea at the time of maximum vegetative growth.

4.9 SOIL EVAPORATION

Micro-lysimeter design

Figure 4.22 shows the design of the micro-lysimeters constructed to measure soil evaporation (e_s). In order to facilitate repeated weighings, the lysimeters were placed inside outer sleeves recessed into the soil at fixed locations for the duration of the measurement period. To minimise differences in the thermal regimes of the soil inside and adjacent to the lysimeter, the gap between the inner and outer sleeves was kept to a minimum. The outer sleeves were constructed from PVC drainpipes of the same internal diameter (ID, 10 cm) as the lysimeters; these were cut to length, heated until malleable in hot oil and extruded on a metal jig to increase the ID by 10 mm, which reduced to approximately 8 mm after cooling. The ID of extruded outer sleeves was

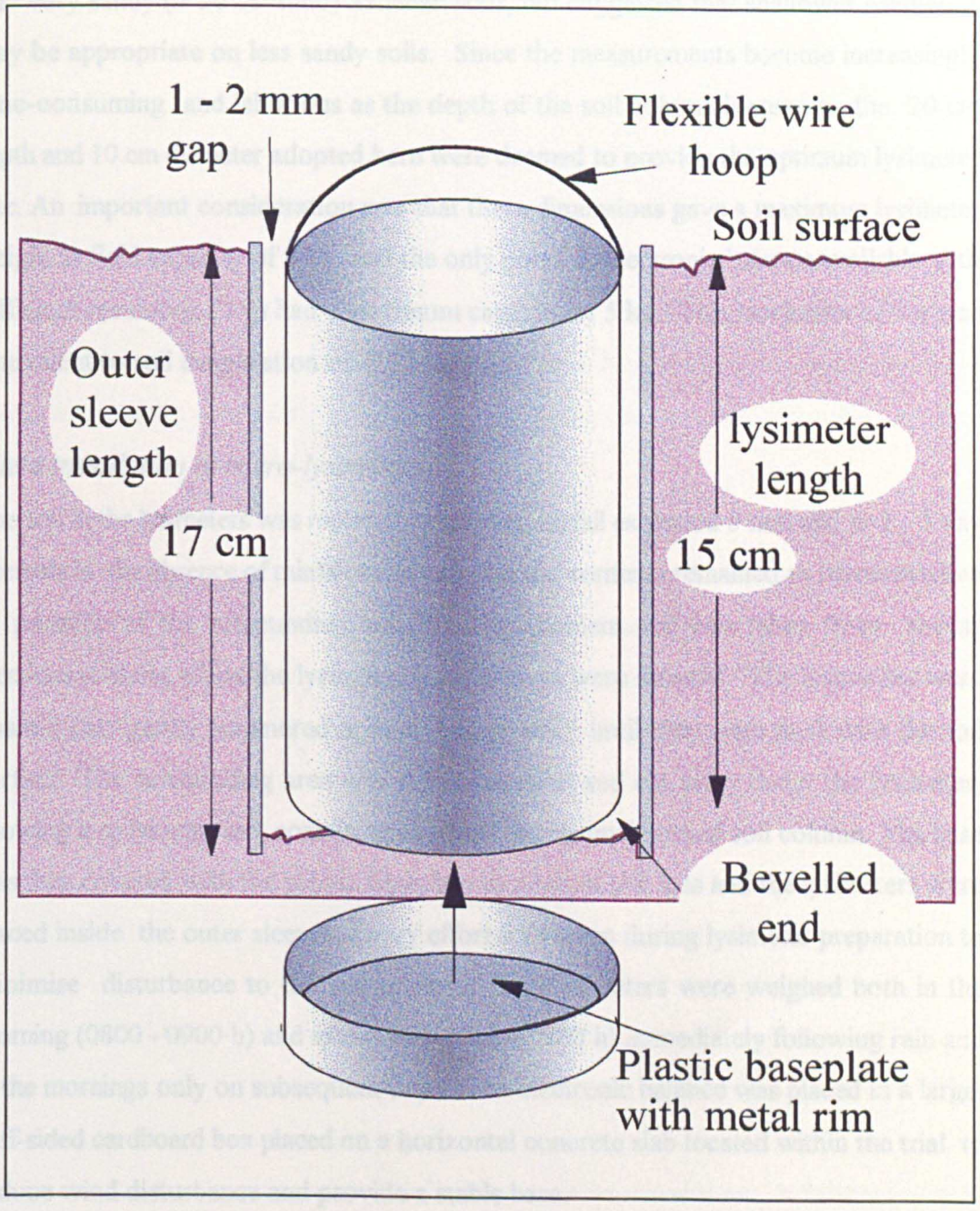


Figure 4.22 Diagrammatic illustration of a micro-lysimeter used for measuring soil evaporation. The lysimeters and outer sleeves were constructed from 10 cm diameter PVC drainpipes. The micro-lysimeters, containing soil columns from locations representative of the outer sleeve sites, were located flush with the soil surface. The flexible wire hoops permitted easy extraction for weighing and were pushed to one side between measurements to minimise interference.

therefore only 2-3 mm greater than the external diameter of the lysimeters.

Daamen (1991) recommended that lysimeters of at least 20 cm in depth should be used for very sandy (> 90 % sand) Sahelian soils, but suggested that shallower lysimeters may be appropriate on less sandy soils. Since the measurements become increasingly time-consuming and laborious as the depth of the soil column increases, the 20 cm depth and 10 cm diameter adopted here were deemed to provide the optimum lysimeter size. An important consideration was that these dimensions gave a maximum lysimeter weight at field capacity of 5 kg and the only portable electronic balance available with sufficient resolution (1 g) had a maximum capacity of 5 kg. This resolution of 1 g was equivalent to soil evaporation of 0.13 mm.

Field installation of micro-lysimeters

The soil in the lysimeters was replaced whenever rainfall exceeded 5 mm and at 3 - 5 day intervals in the absence of rainfall to ensure that the contents remained as representative as possible of the surrounding soil. The replacement soil was taken from similar locations to those where the lysimeter outer sleeves were situated. The lysimeters were pushed (or gently hammered in hard drying soil) until they were flush with the soil surface. The surrounding area was then excavated and cut away under the lysimeter, allowing it to be removed containing an intact, largely undisturbed soil column. The base was then covered with the plastic baseplate to prevent soil loss and the lysimeters were placed inside the outer sleeves. Every effort was taken during lysimeter preparation to minimise disturbance to the soil columns. The lysimeters were weighed both in the morning (0800 - 0900 h) and afternoon (1600 - 1700 h) immediately following rain and in the mornings only on subsequent days. The electronic balance was placed in a large, stiff-sided cardboard box placed on a horizontal concrete slab located within the trial to reduce wind disturbance and provide a stable base.

24 lysimeters were used, with four being placed at random in each of two plots in treatments CTd, Td and Cg. Measurements were carried out between November 1992 and May 1993.

Effects of shade and mulch

Figure 4.23 shows the layout of a trial established on an area of almost level land approximately 100 m uphill from CIRUS in August 1993, in which grevillea mulch was applied at 2.25 and 4.50 t ha^{-1}. The shade nets were of the same design as those used in the main trial during the ensuing short rains (cf. Section 4.6). Each 3.4 x 3.0 m plot received 20 mm of irrigation and the surrounding area was irrigated with a similar (but unmeasured) quantity of water to reduce advective effects on the plots. Irrigation was carried out during late afternoon and early evening (1600 - 2000 h) to provide sufficient time for infiltration prior to lysimeter installation. One micro-lysimeter per plot was weighed and installed early the following morning (0730 - 0900 h) and these were then weighed daily at the same time. Soil evaporation was measured for one week following irrigation, before reirrigating the plots and repeating the process to provide a total of three cycles.

Percentage ground-cover by the mulch was measured using a plumb-line and 10 x 10 cm string grid at the beginning of each irrigation cycle. The grid was fixed approximately 1 m above each plot before lowering the plumb-line at each of the 100 intersections and recording the presence or absence of cover at that point. Two grids were measured for each mulch plot on each the three sampling occasions.

4.10 RUNOFF

20 x 2.5 m runoff sub-plots were installed in three plots each of treatment Td (Fig. 4.2; plots 4, 11 and 14), CTd (plots 5, 10 and 22), Cg (plots 12, 16 and 23) and CTc (plots 6, 9 and 15). Galvanised iron sheeting (30 cm wide) driven vertically into the soil across the top and down the sides of each sub-plot prevented cross-flow. A trough (covered to prevent direct entry of rain) extending across the full width of the down-slope end of each plot channelled the runoff through a pipe into a 1 m^3 collection tank. The tank had sufficient capacity to record 20 mm of runoff in any one event. Runoff water was weighed after every rain event, with subsamples being taken to determine soil losses.

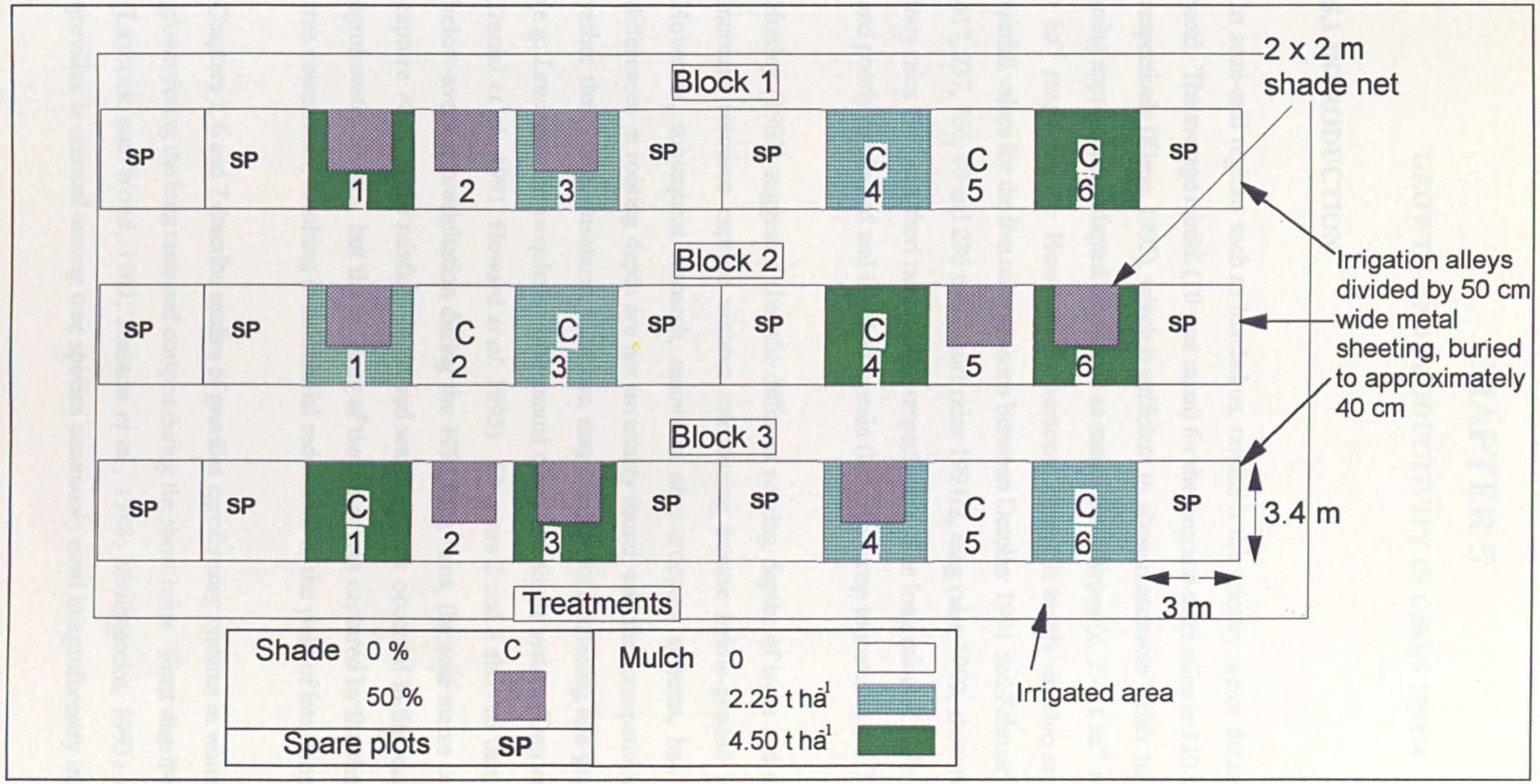


Figure 4.23 Layout of the trial to examine the effect of grevillea mulch and 50 % shade on soil evaporation; mulch was applied at 2.25 and 4.5 t ha^{-1}. The trial was established on an area of almost level land approximately 100 m uphill from CIRUS in August 1993. Each plot received 20 mm of irrigation and the surrounding area was irrigated with a similar (but unmeasured) quantity of water to reduce advective effects on the plots.

CHAPTER 5

GROWTH AND PRODUCTIVITY IN CIRUS 1991/4

5.1 INTRODUCTION

In semi-arid regions such as Machakos, rainfall is the primary factor determining crop yield. The average rainfall (10 year mean) for the long and short rains is 330 and 365 mm respectively (Kiepe, 1995), which is sufficient to allow reasonable yields to be obtained using appropriately adapted crops such as maize and cowpea (c. 2 -3 t ha^{-1} and 0.5 - 1.0 t ha^{-1} respectively). However, the seasonal rainfall is highly variable and the actual rainfall values for the five rainy seasons between October 1991 and February 1994 were 417, 237, 766, 80 and 286 mm (short rains 1991/2, long rains 1992, short rains 1992/3, long rains 1993 and short rains 1993/4 respectively). The long rains of 1993 were sparse and poorly distributed and failed to sustain the maize crop to maturity (cf. Section 4.4).

Huxley (1983) suggested that the different rooting depths of trees and crops would increase resource capture without introducing intense below-ground competition. However, subsequent research, mainly in alley-cropping systems, has shown that differences in rooting depth are not invariably found, and that competition for water, rather than complementarity in its use, may result from combining fast-growing trees (e.g. *Leucaena leucocephala*) with annual crops in a single system (Ong *et al.*, 1991b; Daniel *et al.*, 1991, Howard *et al.* 1995). Chapters 2 and 3 showed that, despite the below-average precipitation during the 1992 long rains, the sole maize crop failed to capture 70 % of the rainfall. Improved water capture occurred in the leucaena/maize agroforestry system, but the majority of the water was captured by the shallow-rooted tree component, resulting in substantial reductions in the yield of intercropped maize.

Chapters 5, 6 and 7 describe studies of grevillea agroforestry systems in which maize was grown during the long rains and cowpea during the short rains. Root distribution studies (Laycock and Wood, 1963; Jonsson *et al.*, 1988; Mwihomeke, 1993) suggest that grevillea is unusual among tree species commonly used in agroforestry in terms of its

predominantly deep rooting habit and spatial complementarity with shallow rooted crops: Laycock and Wood (1963) suggested that competition with tea for water was lower than that from the other tree species studied because of this deep rooting habit. The trial described here (CIRUS) was designed to investigate the complementarity in resource use of the deep-rooted grevillea with comparatively shallow-rooted crops on sloping land. Chapter 5 presents the results for growth and productivity of the grevillea and the crops during the rainy seasons between October 1991 and February 1994.

5.2 GREVILLEA

Table 5.1 shows the mean and maximum heights and basal diameters of the grevillea trees in CIRUS 28 months after planting (February 1994). The grevillea grew rapidly in all treatments (cf. Plates 5.1, 5.2, 5.3 and 5.4) and the mean annual increments of height over this period ranged from 165 cm yr^{-1} in CTc to 205 cm yr^{-1} in Td.

Table 5.1 Mean and maximum heights and basal diameters of grevillea in all treatments (23 February 1994).

	Diameter (cm)		
Treatment	Maximum	Mean	s.e.
Td	13.7	10.13	0.198
CTd	11.8	8.71	0.144
CTc	11.2	7.77	0.201
CTa	13.0	8.69	0.166
	Height (cm)		
Td	673	481.4	9.25
CTd	619	448.9	7.27
CTc	625	389.1	9.44
CTa	660	432.7	7.50

NB. Height was measured to the nearest cm.

Although within-treatment variation in tree size was moderate (c.v. 19-26%), this variation did not appear to be randomly distributed. The total dry weights of the trees in each plot were therefore subjected to regression analysis with respect to treatment and

Plate 5.1 Small grevillea saplings (<30 cm in height, visible in the foreground), 5-6 months after establishment in the CTa treatment of CIRUS, c. 15 days after sowing the maize during the 1992 long rains.

Plate 5.2 Grevillea saplings (<2.0 m in height), c.14 months after establishment in the CTa treatment of CIRUS, during the 1992/3 short rains. The measurement of interception of photosynthetically active radiation by the trees using a ceptometer probe was underway.

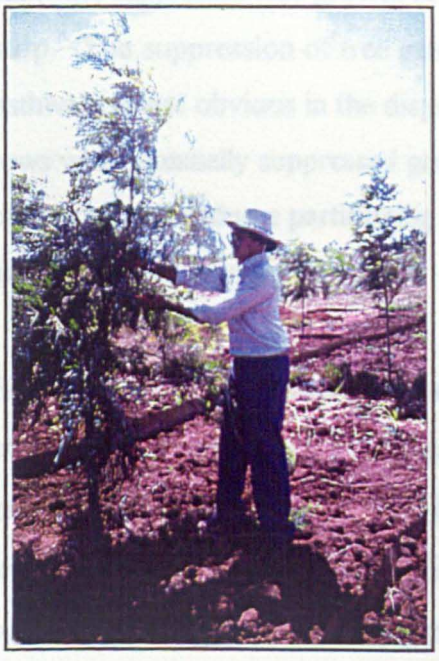


Plate 5.3 The first pruning of the grevillea trees (the trees were c. 3.0 m in height) 19 months after establishment in the sole tree treatment of CIRUS during the 1993 long dry season.

Plate 5.4 Second pruning of the grevillea trees (the trees were a maximum height of >6.5 m), 25 months after establishment in the sole tree treatment of CIRUS, shortly after the 1993/4 short rains (23/2/94).

soil depth (cf. Section 4.4), but tree weight proved not to be significantly correlated with soil depth ($p > 0.3$). Figure 5.1 shows the mean standing biomass for each tree row in all four treatments. In both dispersed treatments (Fig. 5.1a), biomass was lowest in the central row and the values obtained were significantly different from most of the other rows within that treatment (with the exception of row 5 in Td and row 4 in CTd). In the two row-planted treatments (Fig. 5.1b), the central rows form a sharp contrast, with biomass in the across contour-planted treatment being significantly greater ($p < 0.05$) than in any other row in either treatment. The central tree row in each of the contour-planted treatments (Td, CTd and CTc) was planted along the vetiver grass strip used for erosion control and the significant difference in biomass between the central rows in the CTc and CTa treatments (Fig. 5.1b) suggests that the presence of this strip suppressed tree growth. The outer rows of all treatments were within 1 m of the grass walkways until the plots were extended in February 1993. The greater biomass of the central row relative to the outer rows in the CTa treatment suggests that the proximity of the grass pathways suppressed tree growth in a similar but less pronounced fashion to the vetiver strip. The suppression of tree growth as a result of proximity to the vetiver or grass pathways is less obvious in the dispersed treatments. Since the elimination of these tree rows with potentially suppressed growth from further analysis would have distorted the calculations of resource partitioning between trees and crops, the data for all trees were included in the ensuing analyses.

Figure 5.2 shows the standing biomass of trees in all four treatments. Although analysis of variance for total standing biomass per tree showed highly significant treatment effects on all sampling dates ($F_{26\text{-}140, d.f.\ 3, 9}$; $p < 0.001$), the values for the CTd and CTa treatments were not significantly different ($p > 0.1$ - $p > 0.9$). However, when biomass was expressed per unit land area (t ha^{-1}), the differing tree populations of the row and dispersed-planted treatments (555.6 and 833.3 trees ha^{-1} respectively) were sufficient to establish a significant difference between CTd and CTa (Fig. 5.3; $p < 0.05$ - $p < 0.01$).

Table 5.2 shows data for seasonal biomass production in all four treatments expressed both per tree and per unit land area, together with the corresponding mean daily

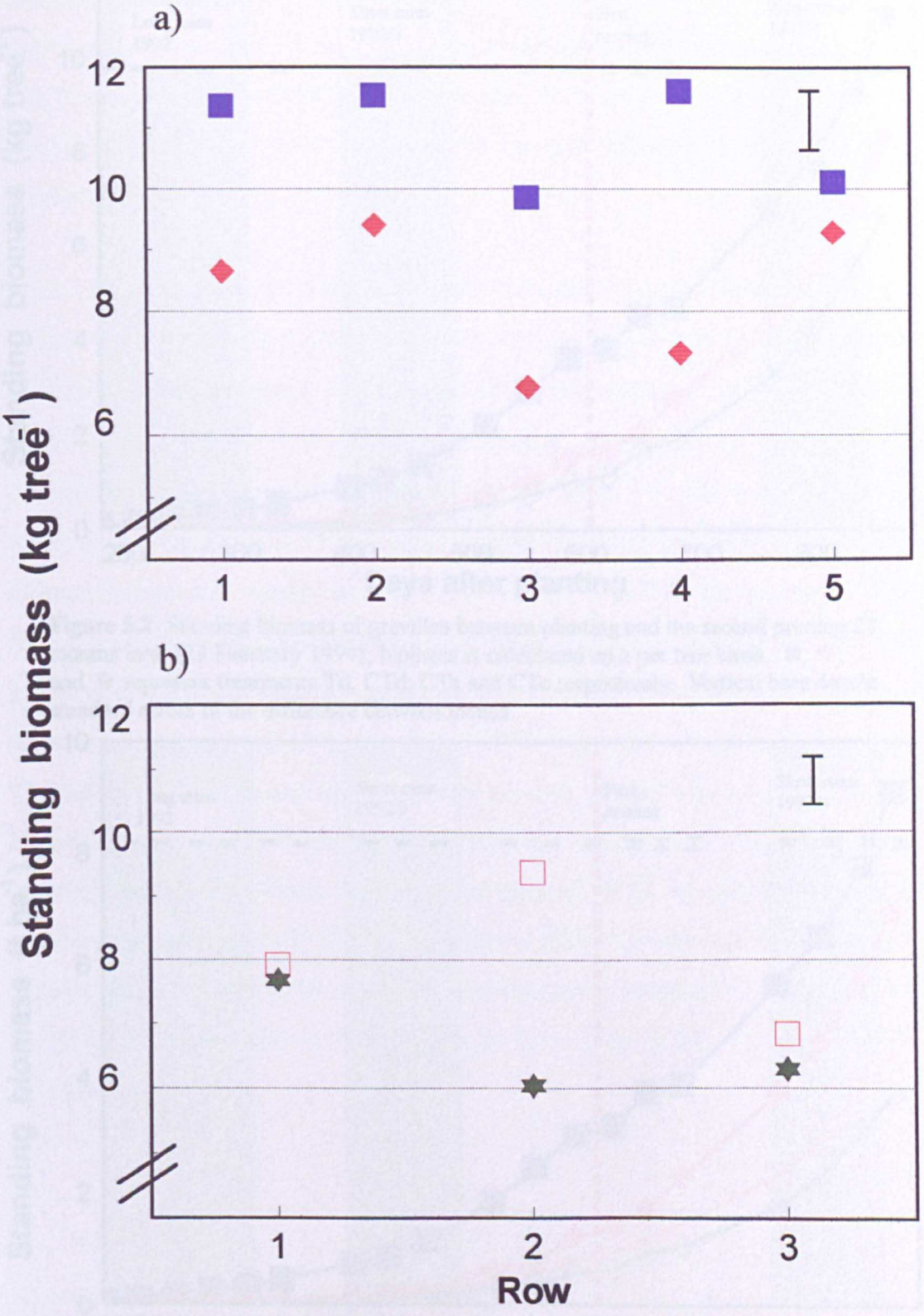


Figure 5.1 Mean standing biomass of grevillea in each of the tree rows on 23 February 1994, 28 months after planting. (a) ■ and ◆ represent the dispersed treatments Td and CTd, with five tree rows per plot; (b) □ and ✶ represent the row-planted treatments CTa and CTc, with three tree rows per plot. Vertical bars denote standard errors of the difference between means.

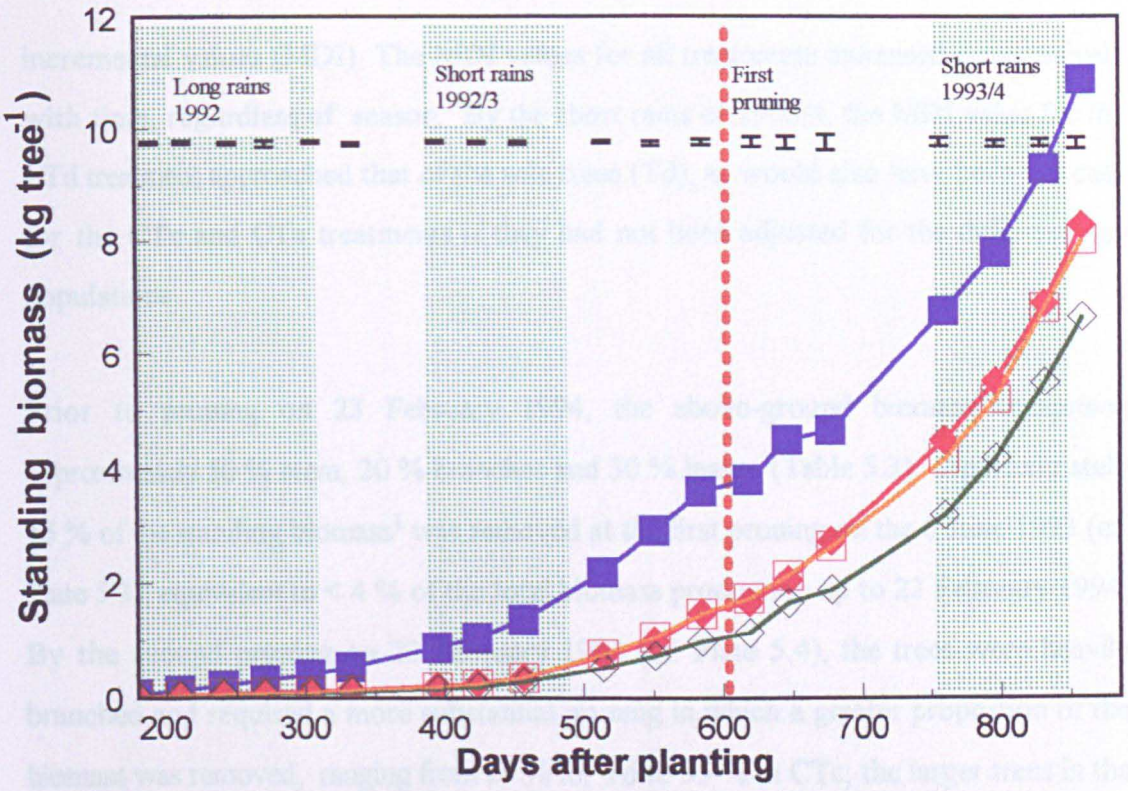


Figure 5.2 Standing biomass of grevillea between planting and the second pruning 28 months later (23 February 1994); biomass is calculated on a per tree basis. ■, ◆, □ and ◇ represent treatments Td, CTd, CTa and CTc respectively. Vertical bars denote standard errors of the difference between means.

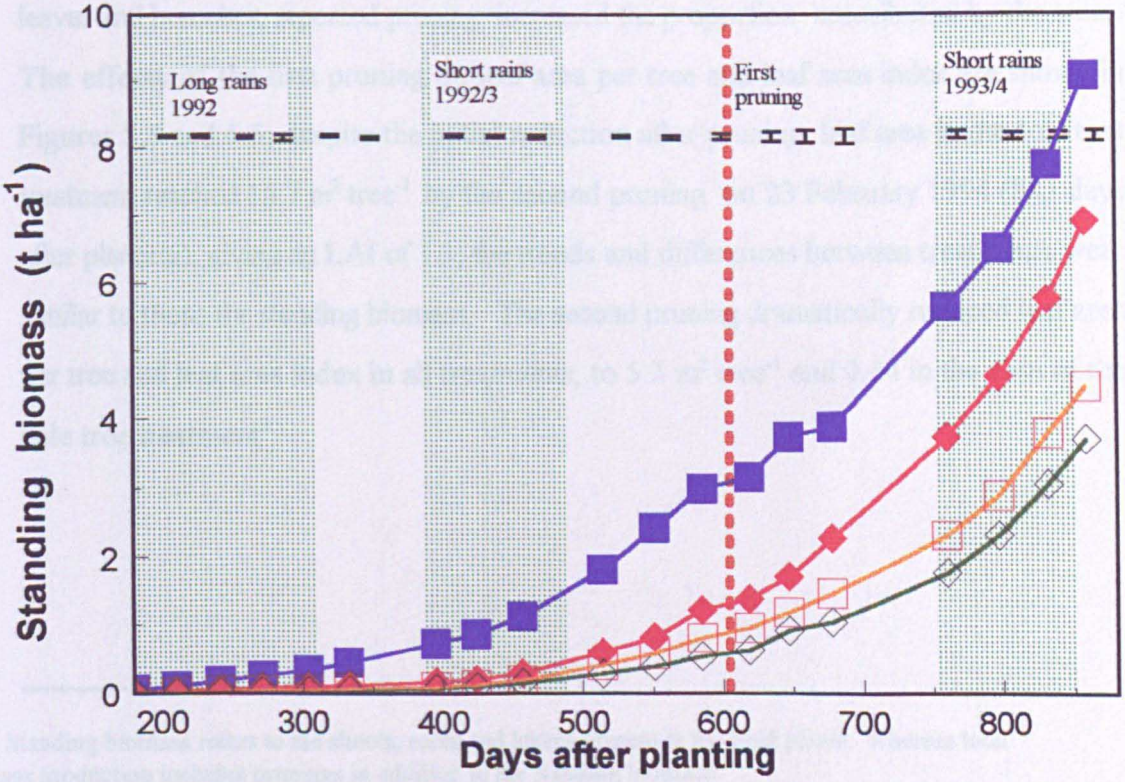


Figure 5.3 Standing biomass of grevillea between planting and the second pruning 28 months later (23 February 1994); biomass is calculated on a system area basis. ■, ◆, □ and ◇ represent treatments Td, CTd, CTa and CTc respectively. Vertical bars denote standard errors of the difference between means.

incremental values (MDI). The MDI values for all treatments increased progressively with time, regardless of season. By the short rains of 1993/4, the MDI value for the CTd treatment approached that of the sole trees (Td), as would also have been the case for the CTc and CTa treatments if they had not been adjusted for the differing tree populations.

Prior to pruning on 23 February 1994, the above-ground biomass comprised approximately 50 % stem, 20 % branches and 30 % leaves (Table 5.3). Approximately 15 % of the standing biomass[1] was removed at the first pruning on the 6 June 1993 (cf. Plate 5.3); equivalent to < 4 % of the total biomass production up to 23 February 1994. By the second pruning on 23 February 1994 (cf. Plate 5.4), the trees were heavily branched and required a more substantial pruning in which a greater proportion of the biomass was removed, ranging from 29 % for Td to 35 % in CTc; the larger trees in the former treatment had a higher proportion of stem, thereby accounting for the smaller proportion of biomass removed. As the prunings at each harvest consisted entirely of leaves and branches, repeated pruning increased the proportion contributed by the stem. The effects of the first pruning on leaf area per tree and leaf area index are shown in Figures 5.4 and 5.5; despite the initial reduction after pruning, leaf area in the sole tree treatment reached 15.7 m^2 $tree^{-1}$ by the second pruning on 23 February 1994 (863 days after planting), giving an LAI of 1.3; the trends and differences between treatments were similar to those for standing biomass. The second pruning dramatically reduced leaf area per tree and leaf area index in all treatments, to 5.3 m^2 $tree^{-1}$ and 0.44 in the case of the sole tree treatment[2].

[1]NB. Standing biomass refers to the shoots, roots and leaves present in the field plants. Whereas total biomass production includes prunings in addition to the standing biomass.

[2]The second pruning on 23 February 1994 marked the end of the current field programme; these data are provided purely to illustrate the severity of the pruning.

Table 5.2 Seasonal biomass production for grevillea. Standard errors are given in parenthesis.

	Season													
	Prior to long rains 1992		Long rains 1992		Long dry season 1992		Short rains 1992/3		Long dry season 1993*		Long dry season 1993 + prunings**		Short rains 1993/4	
Length of season	180		131		73		99		262		262		95	
Treat.	Dry weight (kg tree^{-1})													
Td	0.080	(0.0052)	0.372	(0.0277)	0.374	(0.0329)	0.92	(0.030)	4.64	(0.20)	5.08	(0.28)	3.39	(0.12)
CTd	0.029	(0.0007)	0.102	(0.0047)	0.069	(0.0061)	0.33	(0.026)	3.63	(0.25)	3.91	(0.27)	3.16	(0.17)
CTc	0.024	(0.0027)	0.067	(0.0092)	0.052	(0.0078)	0.25	(0.028)	2.55	(0.22)	2.72	(0.25)	2.91	(0.23)
CTa	0.026	(0.0022)	0.087	(0.0073)	0.064	(0.0109)	0.37	(0.036)	3.34	(0.28)	3.54	(0.28)	3.31	(0.17)
	Dry weight (t ha^{-1})													
Td	0.067	(0.0043)	0.31	(0.0231)	0.311	(0.0274)	0.76	(0.025)	3.87	(0.17)	4.24	(0.23)	2.82	(0.10)
CTd	0.024	(0.0006)	0.085	(0.0040)	0.058	(0.0051)	0.28	(0.022)	3.03	(0.21)	3.26	(0.23)	2.63	(0.14)
CTc	0.013	(0.0015)	0.037	(0.0051)	0.029	(0.0043)	0.14	(0.015)	1.41	(0.12)	1.51	(0.14)	1.62	(0.13)
CTa	0.014	(0.0012)	0.049	(0.0041)	0.035	(0.0060)	0.2	(0.020)	1.85	(0.15)	1.97	(0.15)	1.84	(0.10)
	Mean daily increment (kg ha^{-1})													
Td	0.371	(0.0239)	2.365	(0.1760)	4.267	(0.3760)	7.72	(0.251)	14.77	(0.64)	16.17	(0.88)	29.72	(1.05)
CTd	0.132	(0.0031)	0.647	(0.0303)	0.789	(0.0698)	2.79	(0.218)	11.55	(0.80)	12.44	(0.86)	27.73	(1.45)
CTc	0.074	(0.0083)	0.285	(0.0390)	0.398	(0.0592)	1.42	(0.155)	5.4	(0.46)	5.77	(0.52)	17.01	(1.37)
CTa	0.079	(0.0069)	0.371	(0.0311)	0.486	(0.0825)	2.06	(0.202)	7.07	(0.59)	7.52	(0.58)	19.36	(1.02)

* Due to the failure of the long rains in 1993, the long dry season was assumed to commence after the 1992/3 short rains harvest (12 February 1993) and end at the start of the 1993/4 short rains (1 November 1993).

** Biomass increase during the long dry season including prunings removed on 6 June 1993.

Table 5.3 Leaf, branch, stem and total biomass production of grevillea up to 23 February 1994. Standard errors are given in parenthesis.

	kg tree^{-1}								t ha^{-1}							
	Branches		Leaves		Stems		Total		Branches		Leaves		Stems		Total	
Treat.	Total production upto 23 February 1994 including biomass pruned on 6 June 1993															
Td	1.87	(0.036)	3.49	(0.111)	5.98	(0.176)	11.34	(0.321)	1.56	(0.030)	2.91	(0.093)	4.98	(0.147)	9.45	(0.268)
CTd	1.61	(0.067)	2.94	(0.130)	4.02	(0.370)	8.57	(0.562)	1.34	(0.056)	2.45	(0.108)	3.35	(0.308)	7.15	(0.469)
CTa	1.37	(0.082)	2.47	(0.157)	3.01	(0.252)	6.84	(0.488)	0.76	(0.046)	1.37	(0.087)	1.67	(0.140)	3.8	(0.271)
CTc	1.55	(0.064)	2.81	(0.119)	3.89	(0.363)	8.25	(0.540)	0.86	(0.036)	1.56	(0.066)	2.16	(0.202)	4.58	(0.300)
	Standing biomass prior to pruning on 23 February 1994															
Td	1.8	(0.024)	3.12	(0.042)	5.98	(0.176)	10.9	(0.235)	1.5	(0.020)	2.6	(0.035)	4.98	(0.147)	9.08	(0.196)
CTd	1.56	(0.064)	2.71	(0.111)	4.02	(0.370)	8.3	(0.543)	1.3	(0.053)	2.26	(0.092)	3.35	(0.308)	6.91	(0.452)
CTa	1.34	(0.079	2.32	(0.136)	3.01	(0.252)	6.67	(0.465)	0.74	(0.044)	1.29	(0.076)	1.67	(0.140)	3.71	(0.258)
CTc	1.52	(0.063)	2.64	(0.109)	3.89	(0.363)	8.04	(0.534)	0.85	(0.035)	1.47	(0.061)	2.16	(0.202)	4.47	(0.296)
	Biomass pruned on 23 February 1994															
Td	1.19	(0.083)	2.07	(0.144)	0		3.26	(0.227)	0.99	(0.069)	1.72	(0.120)	0		2.72	(0.190)
CTd	1.01	(0.084)	1.74	(0.146)	0		2.75	(0.231)	0.84	(0.070)	1.45	(0.122)	0		2.29	(0.192)
CTa	0.77	(0.064)	1.36	(0.113)	0		2.13	(0.177)	0.43	(0.036)	0.76	(0.063)	0		1.19	(0.098)
CTc	0.81	(0.014)	1.4	(0.024)	0		2.21	(0.037)	0.45	(0.008)	0.78	(0.013)	0		1.23	(0.021)
	Biomass pruned on 6 June 1993															
Td	0.07	(0.014)	0.37	(0.074)	0		0.44	(0.088)	0.06	(0.011)	0.31	(0.062)	0		0.37	(0.073)
CTd	0.04	(0.007)	0.24	(0.038)	0		0.28	(0.045)	0.04	(0.006)	0.2	(0.031)	0		0.23	(0.037)
CTa	0.03	(0.006)	0.15	(0.031)	0		0.17	(0.037)	0.02	(0.003)	0.08	(0.017)	0		0.1	(0.021)
CTc	0.03	(0.005)	0.18	(0.029)	0		0.21	(0.034)	0.02	(0.003)	0.1	(0.016)	0		0.12	(0.019)

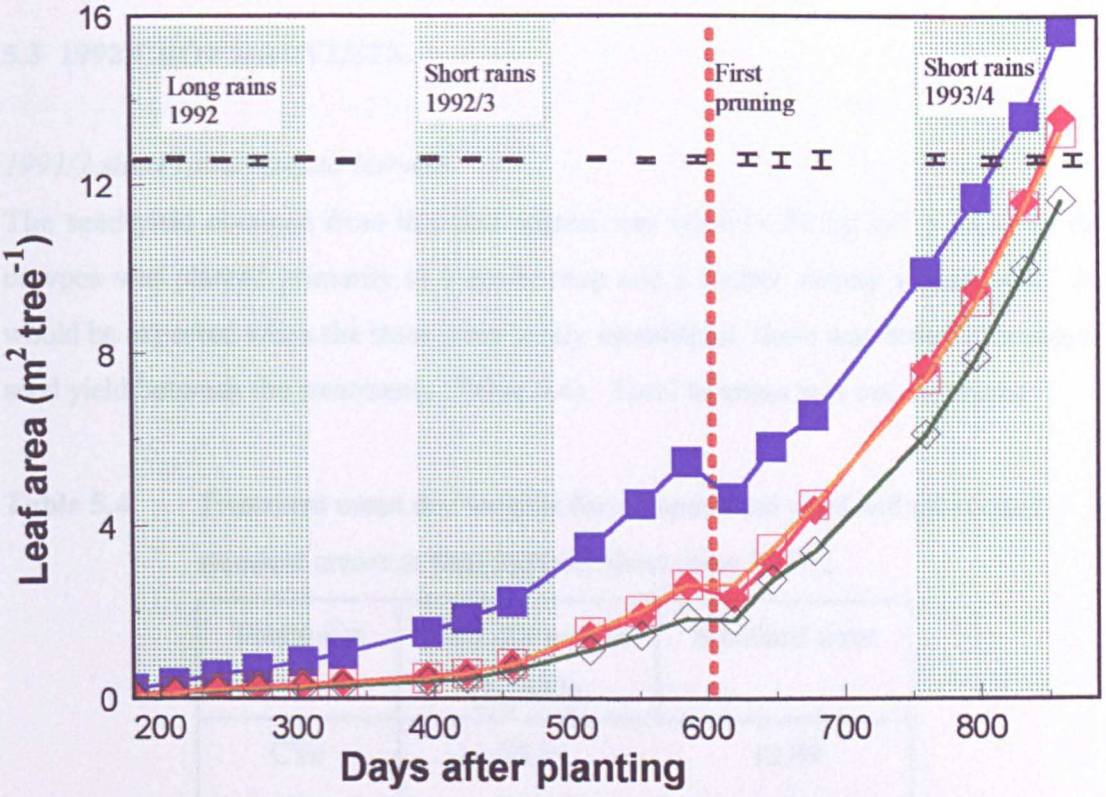


Figure 5.4 Leaf area of grevillea between planting and the second pruning 28 months later (23 February 1994). ■, ◆, □ and ◇ represent treatments Td, CTd, CTa and CTc respectively. Vertical bars denote standard errors of the difference between means.

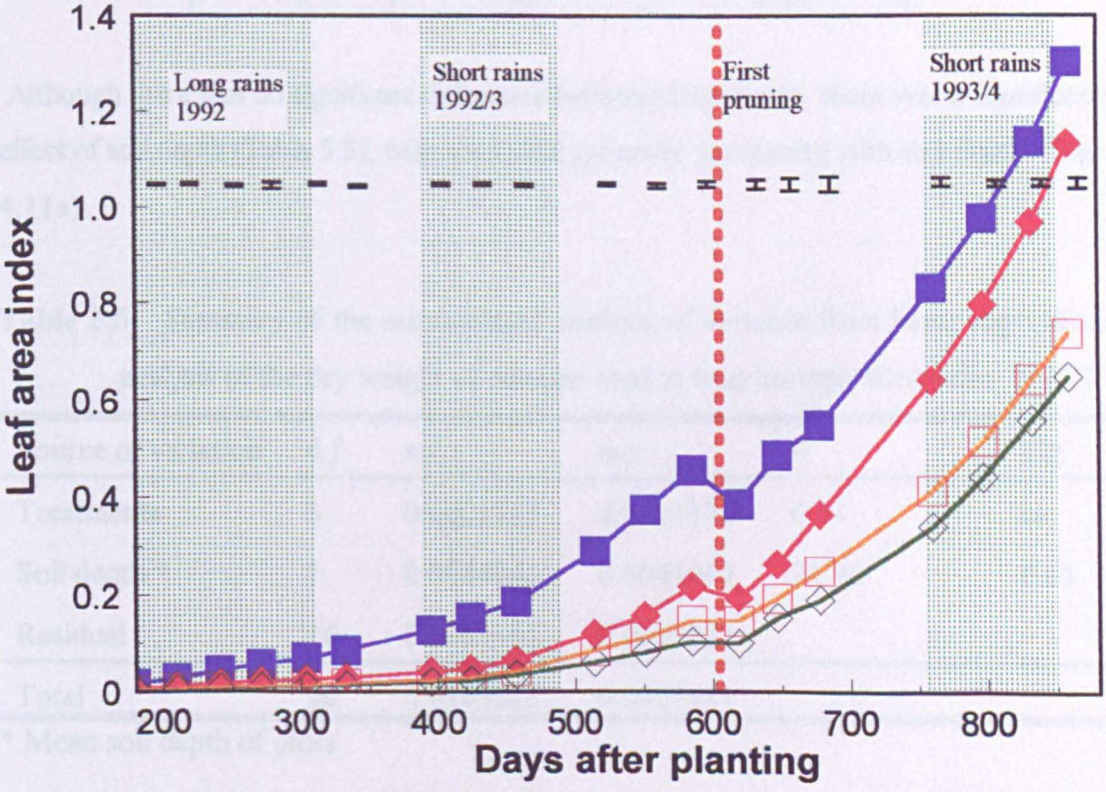


Figure 5.5 Leaf area index of grevillea between planting and the second pruning 28 months later (23 February 1994). ■, ◆, □ and ◇ represent treatments Td, CTd, CTa and CTc respectively. Vertical bars denote standard errors of the difference between means.

5.3 1992 CROP HARVESTS

1991/2 short rains cowpea harvest

The seed yield obtained from this first season was small (< 80 kg ha^{-1}) because the cowpea was planted primarily as a cover crop and a fodder variety was chosen. As would be expected when the trees were barely established, there was little difference in seed yield between the treatments (Table 5.4). Total biomass was not measured.

Table 5.4 Treatment mean dry weights for cowpea seed yield and associated standard errors at final harvest, short rains 1991/2.

Treatment	Seed dry weight (kg ha^{-1})	Standard error
CTc	76.1	12.49
CTa	72.9	12.49
CTd	66.5	11.17
Cg	76.6	8.83

Although there was no significant difference between treatments, there was a significant effect of soil depth (Table 5.5), with seed yield generally increasing with soil depth (Fig. 4.11a).

Table 5.5 Summary of the accumulated analysis of variance from linear regression analysis of the dry weight of cowpea seed at final harvest, short rains 1991/2.

Source of variation	d.f.	s.s.	m.s.	F	Sig.
Treatments	3	0.0003517	0.0001172	0.31	ns
Soil depth *	1	0.0044945	0.0044945	11.76	0.01
Residual	16	0.0061161	0.0003823		
Total	20	0.0109623	0.0005481		

* Mean soil depth of plots

1992 long rains maize harvest

The grain harvest was modest (approximately 1 t ha^{-1}), as could be expected for a season of slightly below average rainfall (237 mm) on an unfertilized site. As for the cowpea in the previous growing season, there was no significant difference in grain yield between treatments (Table 5.6), although there was again a significant effect of soil depth (Table 5.7), with grain yield generally increasing with soil depth (Fig. 4.11b).

Table 5.6 Treatment mean dry weights for maize grain yield and associated standard errors at final harvest, long rains 1992.

Treatment	Grain dry weight (t ha^{-1})	Standard error
CTc	1.03	0.192
CTa	1.20	0.192
CTd	1.18	0.172
Cg	1.25	0.136

Table 5.7 Summary of the accumulated analysis of variance from linear regression analysis of the dry weight of maize grain at final harvest, 1992 long rains.

Source of variation	d.f.	s.s.	m.s.	F	Sig.
Treatments	3	0.1245	0.0415	0.41	ns
Soil depth *	1	0.9043	0.9043	8.96	0.01
Residual	16	1.6144	0.1009		
Total	20	2.6432	0.1322		

* Mean soil depth of the plots

5.4 COWPEA HARVEST AND GROWTH ANALYSIS: 1992/3 SHORT RAINS

Cowpea growth

Figure 5.6 shows the seasonal timecourse for total above-ground dry matter in cowpea in the CTd and Cg treatments. Although no significant differences were detected between treatments, total dry matter increased significantly between harvests until 60 DAS (Table 5.8). Grain and stems accounted for approximately 40 % of total dry matter at final harvest in both treatments. Leaf dry matter reached a maximum at approximately 60 DAS, before falling to near zero by final harvest. The trend for leaf dry matter was reflected by that for leaf area index (LAI, Fig. 5.7); as for total dry matter, there were no significant differences between treatments, but seasonal changes in LAI were significant except between 49 - 60 DAS (Table 5.10). Seasonal mean LAI values were respectively 0.56 and 0.62 for CTd and Cg.

Table 5.8 Significance of changes in total above-ground, pod, leaf and stem dry weights (DWT) and leaf area index (LAI) for cowpea, short rains1992/3.

	Measurement dates compared (DAS)					
	20 - 32	32 - 40	40 - 49	49 - 60	60 - 71	71 - 99
	Probability*					
Total DWT	< 0.05	< 0.001	< 0.001	< 0.01	n.s.	n.s.
Pod DWT	n/a	n/a	n/a	n/a	< 0.05	< 0.001
Stem DWT	n.s.	< 0.01	< 0.001	< 0.001	< 0.05	n.s.
Leaves DWT	< 0.05	< 0.001	< 0.01	< 0.05	< 0.01	< 0.001
LAI	< 0.05	< 0.001	< 0.01	n.s.	< 0.01	< 0.001

* The probability associated with a paired two-tailed t-test; n.s. indicates not significant.

Cowpea yield

Although rainfall was more than double the seasonal average, there was again no significant difference in seed yield between treatments (Tables 5.9 and 5.10). However, in contrast to the previous seasons, there was no significant effect of soil depth (Table 5.10), probably because the abnormally high rainfall ensured that water availability was not a limiting factor for crop growth, even in areas of relatively shallow soil. Some

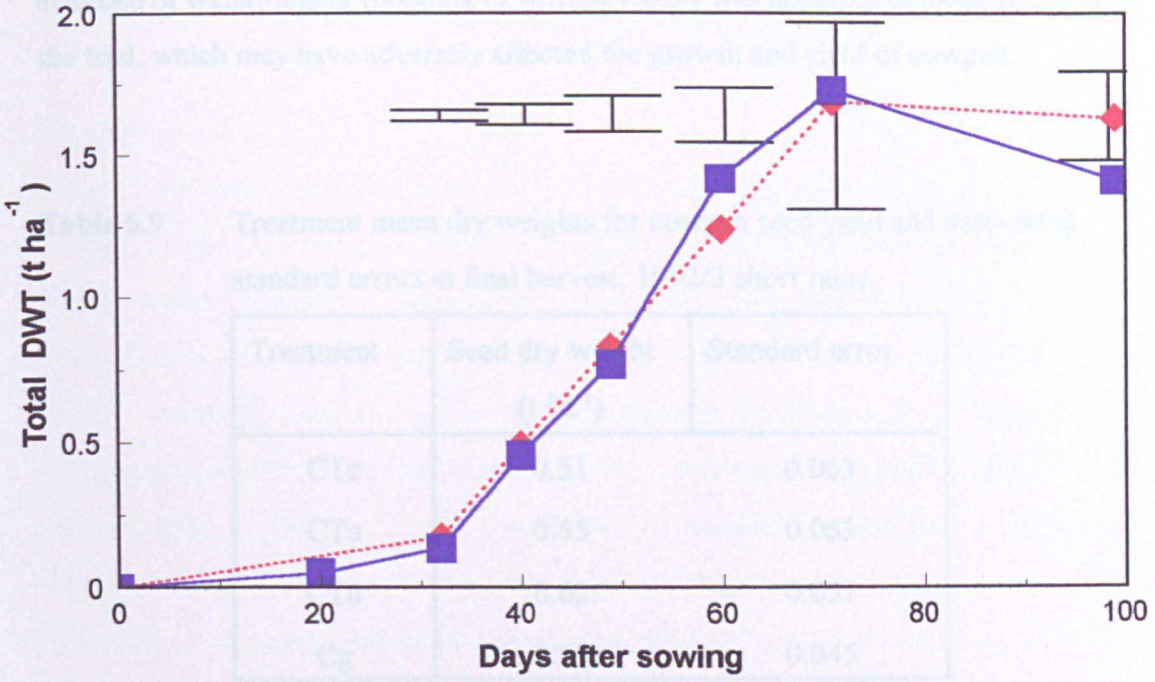


Figure 5.6 Seasonal timecourses of total above-ground dry weight for sole cowpea (■) and CTd cowpea (◆) during the short rains 1992/3. Vertical bars denote standard errors of the difference between means.

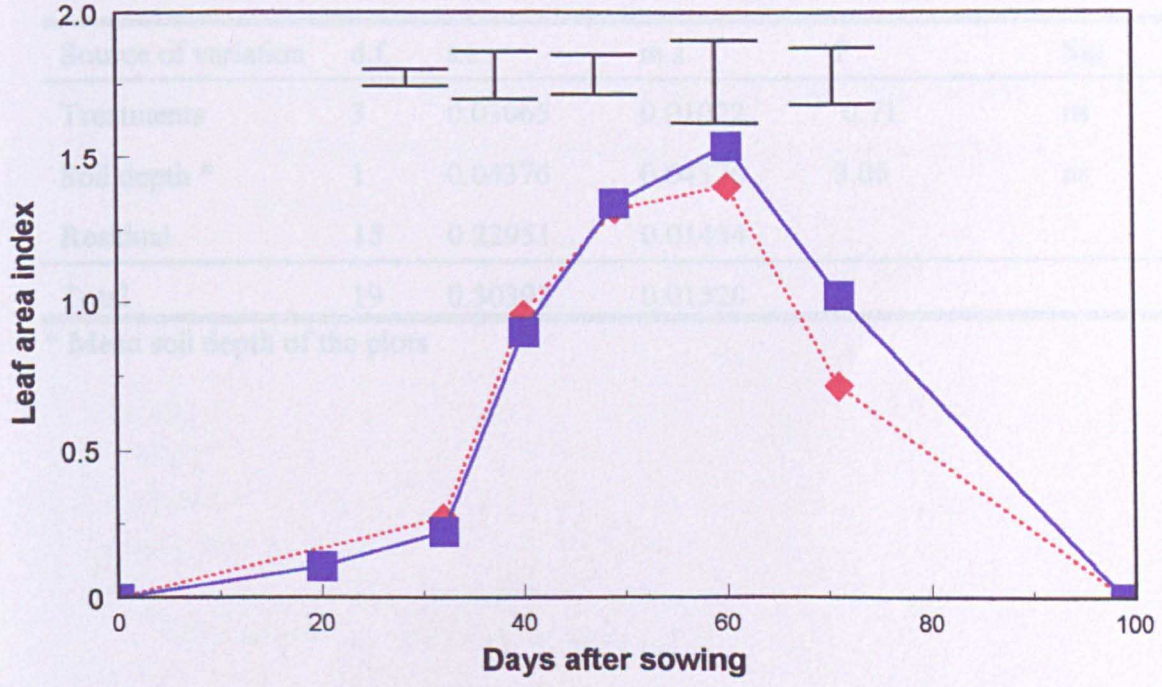


Figure 5.7 Seasonal timecourses of leaf area index for sole cowpea (■) and CTd cowpea (◆) during the short rains 1992/3. Vertical bars denote standard errors of the difference between means.

evidence of waterlogging (ponding of surface water) was apparent in localised areas of the trial, which may have adversely affected the growth and yield of cowpea.

Table 5.9 Treatment mean dry weights for cowpea seed yield and associated standard errors at final harvest, 1992/3 short rains.

Treatment	Seed dry weight ($t\ ha^{-1}$)	Standard error
CTc	0.51	0.063
CTa	0.55	0.063
CTd	0.62	0.057
Cg	0.57	0.045

Table 5.10 Summary of the accumulated analysis of variance from linear regression analysis of the dry weight of cowpea seed at final harvest, 1992/3 short rains.

Source of variation	d.f.	s.s.	m.s.	F	Sig.
Treatments	3	0.03065	0.01022	0.71	ns
Soil depth *	1	0.04376	0.04376	3.05	ns
Residual	15	0.22951	0.01434		
Total	19	0.30392	0.01520		

* Mean soil depth of the plots

5.5 COWPEA HARVEST AND GROWTH: 1993/4 SHORT RAINS

Cowpea growth

Figure 5.8 shows the seasonal timecourses of total above-ground dry matter for cowpea in the CTd and Cg treatments. There were significant differences between treatments on the first two and last two sampling dates ($p < 0.05$, 0.05, 0.05 and 0.001 respectively from t-tests) and increases in total dry matter were significant up to 60 DAS (Table 5.11). Although total dry matter in CTd was only 60 % of that for the sole crop (decreasing to 50% by the end of the season), there were no significant differences in harvest index or the percentage contribution of grain to total dry matter (43.4% and 48.7% for CTd and Cg respectively). As in the previous season, leaf dry matter reached a maximum at approximately 60 DAS before falling to zero by the final harvest. The trend for leaf dry matter was reflected by that for leaf area index (LAI, Fig. 5.9); differences between the treatments were significant at 25, 37 and 63 DAS ($p < 0.05$). Analysis of the seasonal treatment means showed significant effects ($p < 0.01$ from a paired t-test), with seasonal mean LAI values of 0.32 and 0.45 for CTd and Cg respectively.

Table 5.11 Significance of changes in total above-ground, pod, leaf and stem dry weights (DWT) and leaf area index (LAI) for cowpea during the 1993/4 short rains.

	Measurement dates compared (DAS)					
	25 - 37	37 - 45	45 - 52	52 - 63	63 - 73	73 - 96
	Probability*					
Total DWT	< 0.01	< 0.05	< 0.05	< 0.05	< 0.001	< 0.01
Pod DWT	-	-	-	-	-	< 0.01
Stem DWT	< 0.01	< 0.05	< 0.01	< 0.05	< 0.001	< 0.001
Leaves DWT	< 0.05	< 0.05	ns	ns	ns	< 0.001
LAI	< 0.001	ns	ns	ns	ns	< 0.001

* Probability associated with a paired t-test.

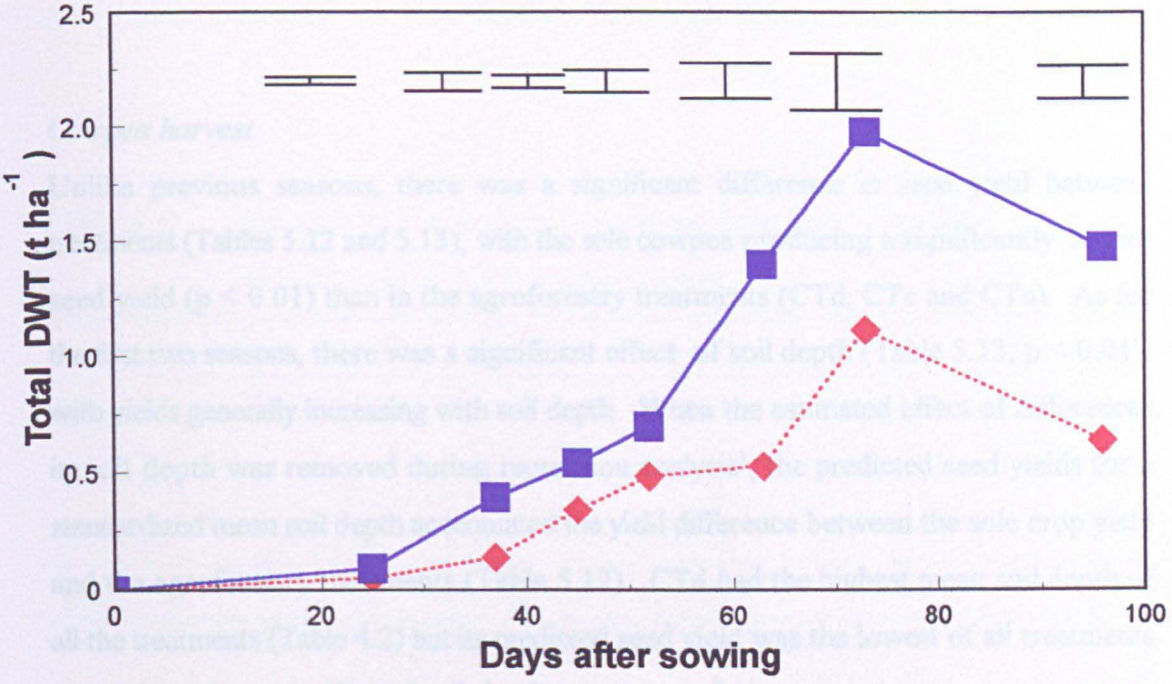


Figure 5.8 Seasonal timecourses of total dry weight for sole cowpea (■) and CTd cowpea (◆) during the short rains 1993/4. Vertical bars denote standard errors of the difference between means.

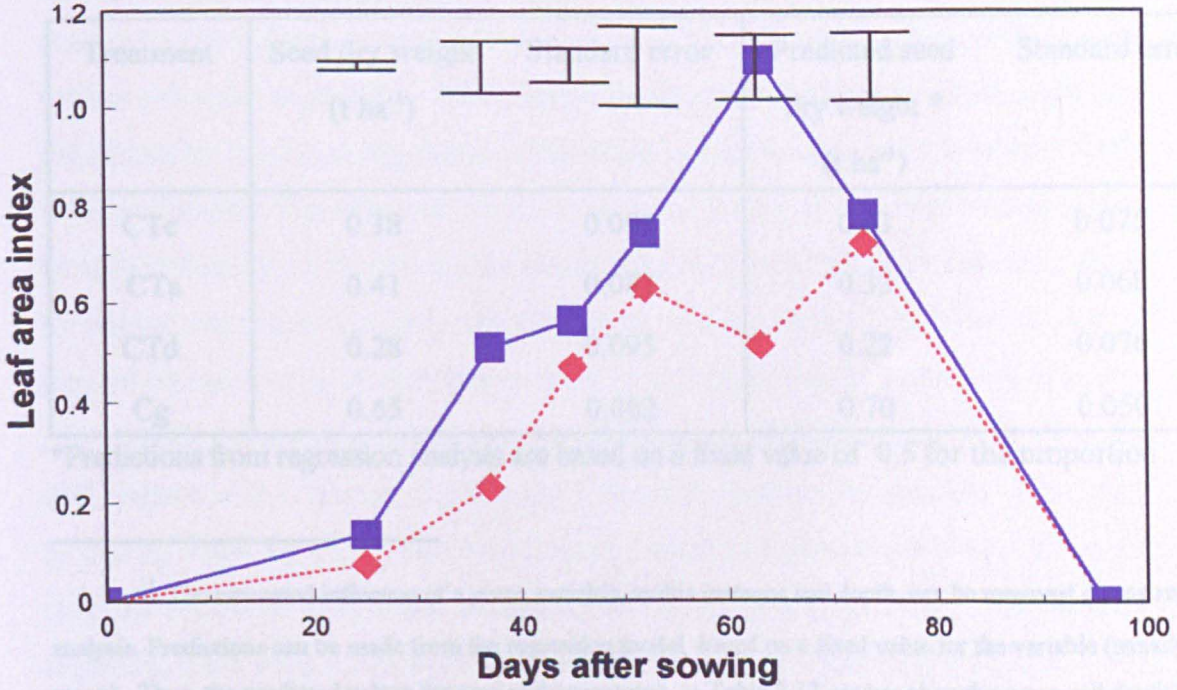


Figure 5.9 Seasonal timecourses of leaf are index for sole cowpea (■) and CTd cowpea (◆) during the short rains 1993/4. Vertical bars denote standard errors of the difference between means.

Cowpea harvest

Unlike previous seasons, there was a significant difference in seed yield between treatments (Tables 5.12 and 5.13), with the sole cowpea producing a significantly higher seed yield ($p < 0.01$) than in the agroforestry treatments (CTd, CTc and CTa). As for the first two seasons, there was a significant effect of soil depth (Table 5.13; $p < 0.01$), with yields generally increasing with soil depth. When the estimated effect of differences in soil depth was removed during regression analysis[1], the predicted seed yields for a standardized mean soil depth accentuated the yield difference between the sole crop yield and the agroforestry treatments (Table 5.12). CTd had the highest mean soil depth of all the treatments (Table 4.2) but its predicted seed yield was the lowest of all treatments when the estimated effect of soil depth was removed.

Table 5.12 Treatment mean seed dry weights and predicted* mean seed yield for cowpea at final harvest and associated standard errors, 1993/4 short rains.

Treatment	Seed dry weight ($t\ ha^{-1}$)	Standard error	Predicted seed dry weight * ($t\ ha^{-1}$)	Standard error
CTc	0.38	0.095	0.43	0.075
CTa	0.41	0.083	0.33	0.068
CTd	0.28	0.095	0.22	0.076
Cg	0.65	0.062	0.70	0.050

*Predictions from regression analysis are based on a fixed value of 0.5 for the proportion

[1] The estimated influence of a given variable, in this instance soil depth, can be removed during regression analysis. Predictions can be made from the regression model based on a fixed value for the variable (usually the mean). Thus, the predicted values for seed yield presented in Table 5.12 are based on the mean soil depth for all plots.

of the plot with a soil depth less than 71.2 cm (the overall mean soil depth of the trial).

Table 5.13 Summary of the analysis of variance from linear regression analysis of seed dry weight, 1994 cowpea harvest.

Source of variation	d.f.	s.s.	m.s.	F	Sig.
Treatments	3	0.3734	0.1245	7.76	0.01
Soil depth *	1	0.1613	0.1613	10.05	0.01
Residual	12	0.1925	0.0161		
Total	16	0.7272	0.0392		

* Proportion of the plot with a soil depth of less than 71.2 cm

Although soil depth and treatment effects accounted for almost 60 % of the variation in cowpea yield, a considerable proportion of the variation remained unaccounted for. Although not apparently dependent on soil depth, biomass production by grevillea during this season (Table 5.2) was affected by other factors such as competition from the grass pathways and vetiver strips, wind damage, and possibly by localised differences in fertility and water availability; these factors resulted in differences in grevillea biomass production for the season (G_b) between individual replicates of up to 22% relative to the treatment means. The extent of the effect of grevillea on cowpea may be expected to be related directly to the production of grevillea because of the increased competition for natural resources. Similarly, the availability of below-ground resources to cowpea may be expected to be directly proportional to soil depth (or, on a plot level, inversely related to the proportion of the plot with a soil depth less than the mean soil depth of the trial, defined as P_s). Hence, if the mean biomass production by grevillea is multiplied by the P_s value for each plot, this should provide an approximate index (I_r) of the potential reduction in resource availability to the cowpea (Fig. 5.10). As might be expected, seed yield for cowpea was strongly correlated with I_r ($r^2 = 0.84$, $n = 10$), decreasing as I_r increased. To permit the inclusion of the sole crop plots in the analysis, multiple linear regression of cowpea yield on P_s and G_b and their quadratics was carried

out and, the following equation was selected on basis of goodness of fit:

$$Y_c = a - bG_b - cP_s^2 \qquad \textbf{(Eq.5.1)}$$

where Y_c denotes cowpea seed yield, a = 0.940, b = 0.202 and c = 0.728 (s.e. 0.0588, 0.0222 and 0.131 respectively, v.r. 43.14, d.f. 2 , 13, 84.9% of variation accounted for). The fitted values from this equation are shown in Figure 5.11 and extrapolation gives a yield of 0.94 t ha^{-1} when G_b and P_s are zero, which is close to the maximum sole crop yield (0.92 t ha^{-1} when $P_s = 0.15$). Extrapolation also gives a calculated yield of zero when P_s is zero and G_b is 4.5 t ha^{-1} or when P_s is 1 and G_b is 1.0 t ha^{-1}. This equation clearly has limited predictive value since it is specific to this particular season and site, but it does indicate the importance of interactions between tree productivity and soil depth and their potential impact on crop yield.

The reduction in cowpea seed yield in the agroforestry treatments was strongly dependent on the proximity of the grevillea, as indicated by Figure 5.12a which shows the almost linear reduction in crop yields with increasing proximity to the tree rows in the CTc and CTa treatments. Linear regression of crop yield against distance from the tree row demonstrated highly significant relationships for both treatments (r^2 = 0.97 and 0.88, n = 10 and 5 for CTc and CTa respectively). The relationship between crop yield and distance from the tree row was similar in both treatments and there were no significant differences in either the slopes or the constants of the lines of best fit; the data for both treatments were therefore combined and the line of best fit was calculated as:

$$Y_p = a + bx \qquad \textbf{(Eq.5.2)}$$

where Y_p is the cowpea seed yield expressed as a proportion of the overall mean seed yield for the sole crop, x is the distance from the tree row (m), a = 0.396 and b = 0.116 (s.e. 0.0263 and 0.0096 respectively, v.r. 146.78, d.f. 1 , 13, 91.9% of variation accounted for; Fig 5.12b.). Extrapolating from this equation gives $Y_p = 1$, the point at which there is no longer any apparent competition from the tree row; this occurred at a distance of 5.2 m from the trees. The cowpea plants in the CTd treatment, with its 3 by 4 m grevillea spacing, were generally much closer to the trees than in the CTa and CTc treatments, as is reflected by Figure 5.13. CTd cowpea yield exceeded 60 % of

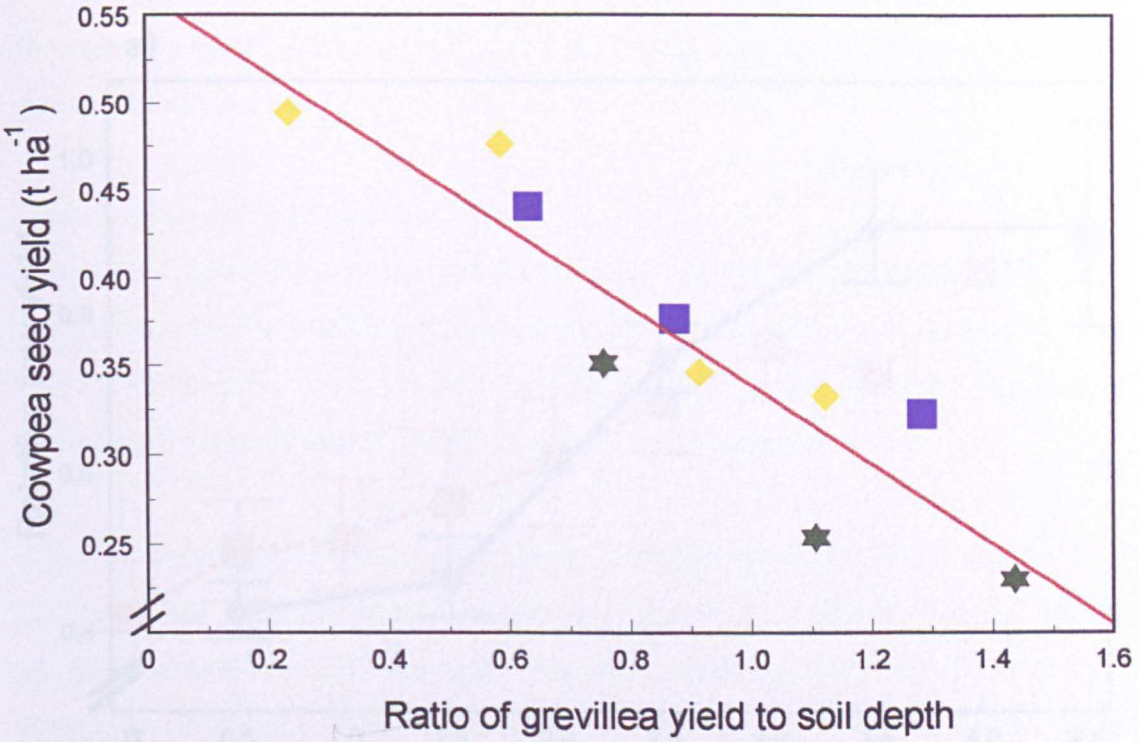


Figure 5.10 Relationship between cowpea seed yield and the ratio of grevillea biomass production:soil depth (the proportion of the plot with a soil depth less than the overall mean depth of the trial) during the short rains 1993/4. ■, ◆ and ✶ represent treatments CTc, CTa and CTd respectively. The regression line is $y = 0.562 - 0.223x$ ($r^2 = 0.84$).

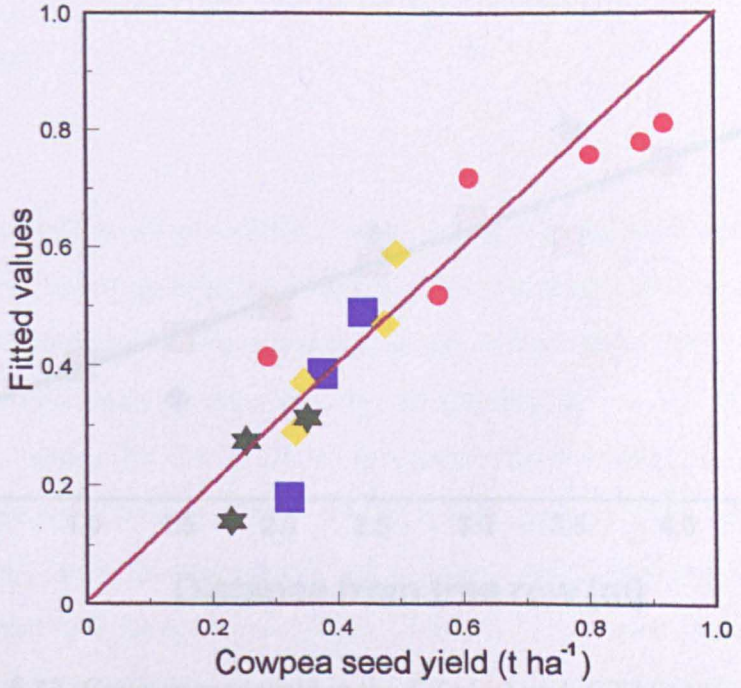


Figure 5.11 Relationship between cowpea seed yield and the fitted values obtained from multiple linear regression of grevillea biomass production against soil depth (the proportion of the plot with a soil depth less than the overall mean depth of the trial) during the short rains 1993/4. ●, ■, ◆ and ✶ represent treatments Cg, CTc, CTa and CTd respectively (see text for the regression equation and a more detailed explanation).

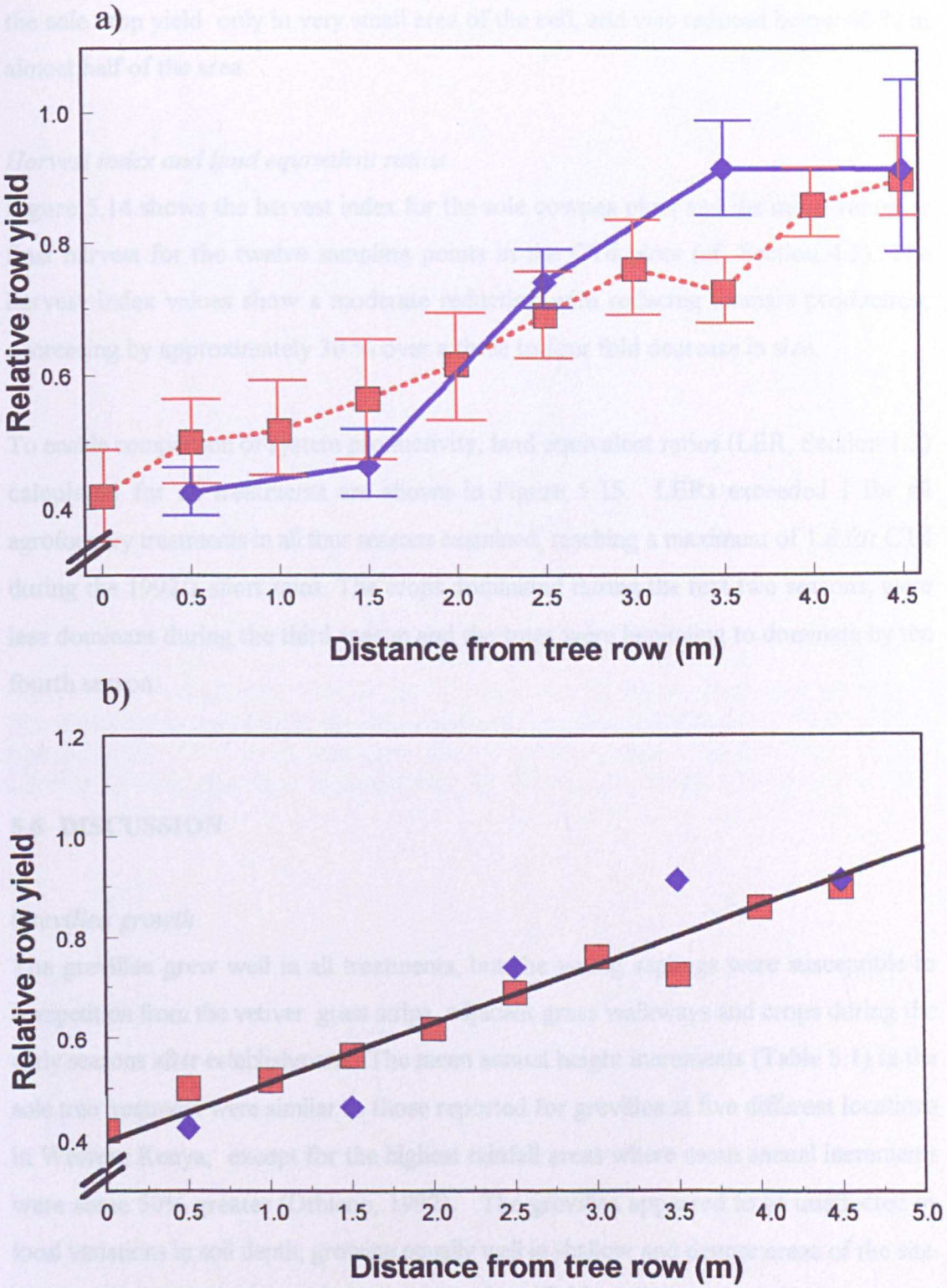


Figure 5.12 Cowpea seed yield in the CTc (■) and CTa (◆) treatments during the short rains 1993/4. (a) The seed yield for the crop rows represented as a proportion of the mean sole crop yield. Vertical bars denote double standard errors of the means. (b) The regression line for the curves plotted in (b) is $y = 0.116x + 0.396$, ($r^2 = 0.92$).

the sole crop yield only in very small area of the cell, and was reduced below 40 % in almost half of the area.

Harvest index and land equivalent ratios

Figure 5.14 shows the harvest index for the sole cowpea plots and the mean values at final harvest for the twelve sampling points in the CTd plots (cf. Section 4.5). The harvest index values show a moderate reduction with reducing biomass production, decreasing by approximately 30 % over a three to four fold decrease in size.

To enable comparison of system productivity, land equivalent ratios (LER, Section 1.3) calculated for all treatments are shown in Figure 5.15. LERs exceeded 1 for all agroforestry treatments in all four seasons examined, reaching a maximum of 1.8 for CTd during the 1992/3 short rains. The crops dominated during the first two seasons, were less dominant during the third season and the trees were beginning to dominate by the fourth season.

5.6 DISCUSSION

Grevillea growth

The grevillea grew well in all treatments, but the young saplings were susceptible to competition from the vetiver grass strips, adjacent grass walkways and crops during the early seasons after establishment. The mean annual height increments (Table 5.1) in the sole tree treatment were similar to those reported for grevillea at five different locations in Western Kenya, except for the highest rainfall areas where mean annual increments were some 50% greater (Othieno, 1992). The grevillea appeared to be unaffected by local variations in soil depth, growing equally well in shallow and deeper areas of the site. Mean daily increments in biomass production (Table 5.2) increased from season to season and the maximum potential growth rate may well not have been reached by the time of second pruning on 23 February 1994, 863 days after planting. By the short rains of 1993/4, the mean daily biomass increments for the trees in the agroforestry treatments approached those for the sole trees, suggesting that the trees were beginning to dominate

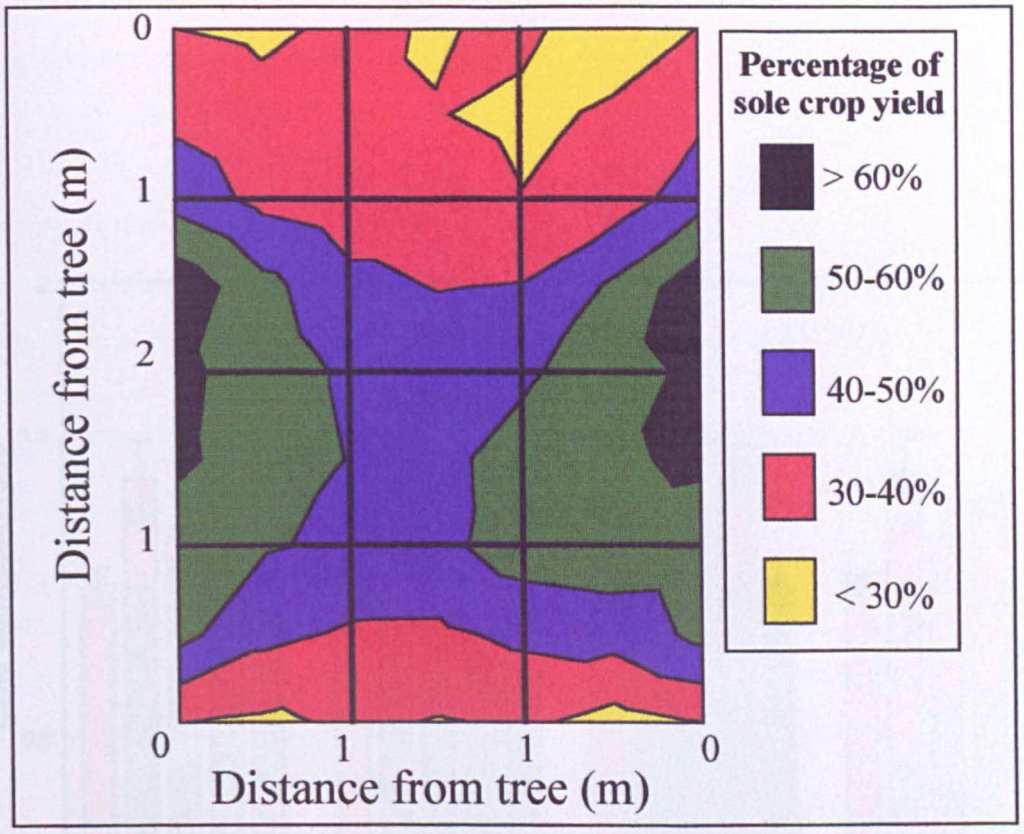


Figure 5.13 Cowpea seed yield in the CTd treatment during the short rains 1993/4. The seed yield is represented as a percentage of the mean sole crop yield. The rectangle represents the 3 by 4 m cell with a grevillea tree at each corner. The data were based on the final harvest taken from approximately 30 cells sampled across the four replicates.

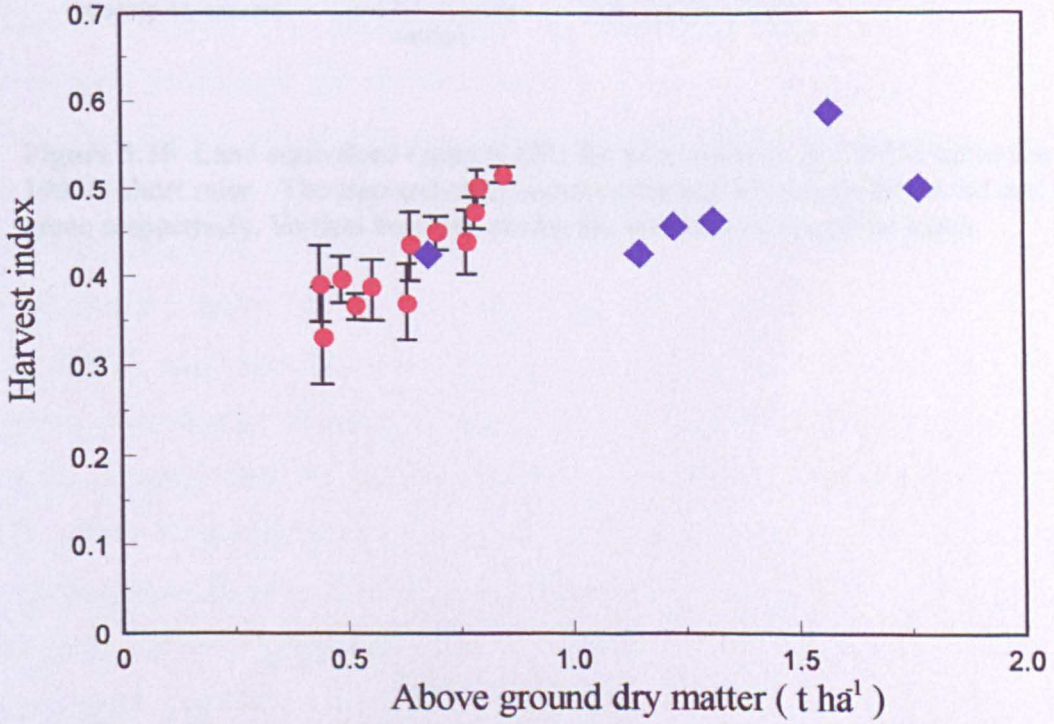


Figure 5.14 Relationship between harvest index (HI) and total cowpea dry matter production at final harvest during the short rains 1993/4. Cg HI values (◆) are the total seed yields of plots divided by the total above-ground dry matter per plot. CTd values (●) are the mean values for the various sampling points (see text). The vertical bars represent double standard errors of the means.

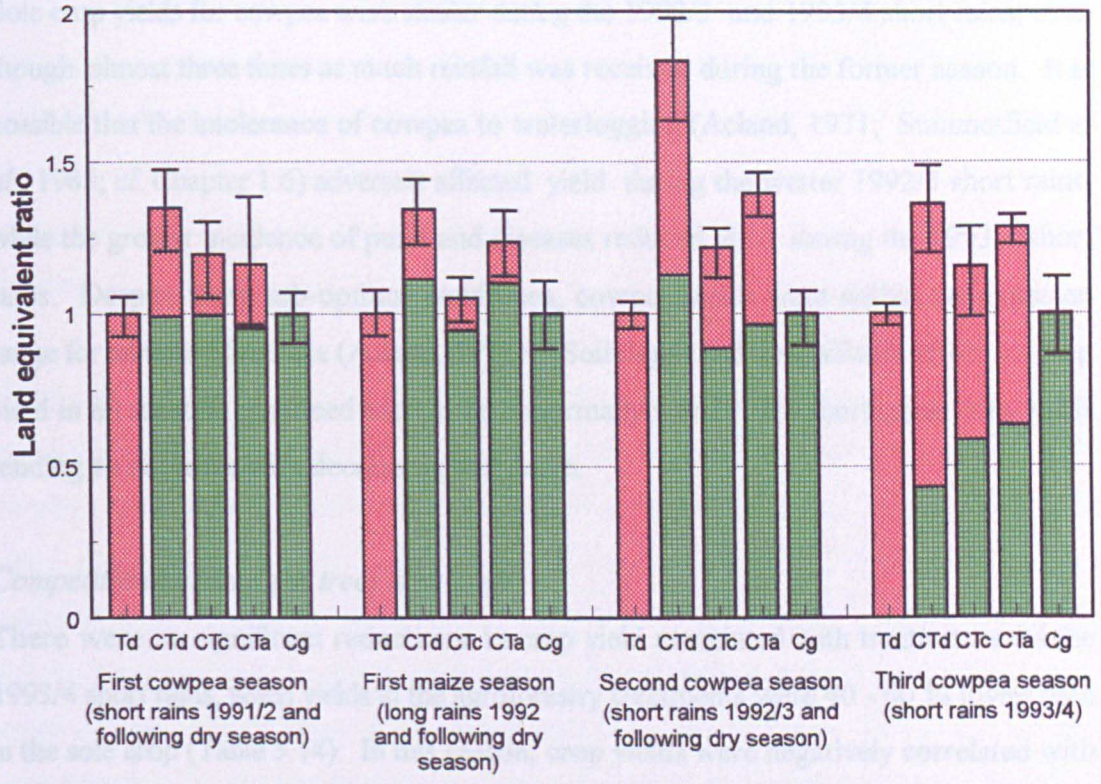


Figure 5.15 Land equivalent ratios (LER) for all treatments in CIRUS up to the 1993/4 short rains. The tree and crop components of LER are shown in red and green respectively. Vertical bars denote double standard errors of the mean.

the system and that competition from the crops was of decreasing importance.

Cowpea growth

Sole crop yields for cowpea were similar during the 1992/3 and 1993/4 short rains, even though almost three times as much rainfall was received during the former season. It is possible that the intolerance of cowpea to waterlogging (Acland, 1971; Summerfield *et al.*, 1985; cf. Chapter 1.6) adversely affected yield during the wetter 1992/3 short rains, while the greater incidence of pests and diseases reduced yield during the 1993/4 short rains. Despite these sub-optimal conditions, cowpea yields were within the expected range for an unfertilized site (Acland, 1971). Soil depth had a significant effect on crop yield in all seasons examined except the abnormally wet 1992/3 short rains, with yields tending to decrease with decreasing soil depth.

Competition between the trees and crops

There were no significant reductions in crop yield associated with treatment until the 1993/4 short rains, when yields in the agroforestry treatments were 40 - 60 % lower than in the sole crop (Table 5.14). In this season, crop yields were negatively correlated with tree biomass production and positively correlated with soil depth (Eq. 5.2). If not incorporated into any analysis of productivity, systematic variations in soil depth might well obscure or enhance treatment effects; where possible, therefore, a thorough survey of soil depth should be undertaken after site clearance and the results incorporated into the experimental design when setting up new experimental trials. Thus at final harvest in the 1993/4 short rains, the relatively high mean soil depth within the CTd plots appeared to ameliorate the effect of competition from the trees, apparently accounting for a 20 % higher yield than that predicted for a standardized mean soil depth (Table 5.12). Of the three agroforestry treatments, CTd had the highest tree population and hence the greatest biomass production by grevillea (Table 5.2) and the lowest cowpea yield during the 1993/4 short rains. However, despite the lower biomass production of the trees in the row-planted treatments, competition reduced crop yields across the entire plot, even at a distance of 4.5 m from the tree rows.

Land equivalent ratios

The land equivalent ratios (LER, cf. Section 1.3) in the agroforestry systems were consistently > 1 in all cropping seasons (Fig. 5.15). The lower LERs of CTa and CTc compared with CTd are a consequence of their sub-optimal tree populations, although this was largely compensated for in the final season by larger crop yields. The shifting competitive balance between the trees and crops can be clearly seen, since the crops dominated during the first two seasons, were less dominant during the third season and the trees were beginning to dominate by the fourth season. The nature of the changing competitive balance and the implications for local farmers are discussed further in Chapter 8.

Ong *et al.* (1996) suggested that when mixtures of competing species are used there is no yield advantage to be gained from varying the proportions of the components of the mixture. Rao (1992b) illustrated the absence of any yield advantage when leucaena was alley cropped with a pearl millet (*Pennisetum glaucum* L. Br.)/pigeonpea (*Cajanus cajan*, L. Millsp) intercrop, castor (*Ricinus communis*) or groundnut (*Arachis hypogea* L.); he concluded that the alley cropping systems were, at best, only as productive as sole crops or block-planted systems due to competition for soil moisture. Similar conclusions were reached for the leucaena/maize system examined in the ABG trial (cf. Chapters 2 and 3) and the leucaena/sorghum system described by Singh *et al.* (1989).

Increases in resource capture or the efficiency of resource use in mixtures relative to the corresponding sole crops and LER values > 1 have been reported for both intercropping (Willey *et al.*, 1986) and agroforestry systems. Ong *et al.* (1996) reported overyielding in a *Cassia spectabalis*/cowpea system which resulted from improved light capture and conversion efficiency in the mixture relative to the sole trees and crops. Stigter and Baldy (1995) stated that the spatial and temporal heterogeneity in intercropping permits far greater manipulation of the microclimate than in monocropping. Changes in resource use efficiency cannot occur without some modification of the microclimatic or edaphic conditions experienced by the components of an intercrop or agroforestry system. The overyielding of the grevillea/crop mixtures in CIRUS is likely to have resulted predominantly from increases in resource capture during the first three cropping seasons

when the tress were still small (generally < 2 m in height), cast little shade (c. 5 % in the CTd treatment) and were therefore incapable of substantially altering the microclimatic conditions experienced by the understorey crop. However, by the 1993/4 short rains, the trees were much larger (c. 5 m in height) and cast much more shade (c. 30 % in the CTd treatment); the microclimatic modifications experienced by the understorey crops would therefore be expected to be correspondingly greater than in previous seasons. Thus, the overyielding observed in the grevillea/crop mixtures during the 1993/4 short rains may well have resulted from a combination of improved resource capture and resource use efficiency. Changes in resource capture and conversion efficiency are discussed in greater detail in Chapters 6 and 7.

CHAPTER 6

LIGHT CAPTURE AND UTILISATION

6.1 INTRODUCTION

The principles involved in the capture and utilisation of light in sole crops have been the subject of extensive research and are now well understood (Squire, 1990; Jones, 1992; Ong *et al.*, 1996). However, the understanding and application of these principles in mixed cropping systems is much less advanced, largely because of the much greater spatial and temporal complexity of such systems. Similarly, the complexities of studies of the capture and utilisation of light by trees is made much more complex by the increased scale of such measurements (Cannell, 1989; Ong *et al.*, 1996). Previous research of resource capture by mixed cropping and agroforestry systems has concentrated primarily on line planting or alley cropping arrangements (Marshall and Willey, 1983; Azam-Ali *et al.*, 1990; Wallace *et al.*, 1991; Corlett *et al.*, 1992). The present chapter presents results for a more complex system in which the understorey crops were grown under dispersed planted trees.

Alterations in the capture and utilisation of light in agroforestry systems have already been shown to have a major impact on the yield of the crop component. For example, the results presented in Chapter 3 showed that yield in the C4 species, maize, decreased almost linearly as shade increased. The leucaena intercepted over 80% of total incoming radiation close to the base of the tree, whereas grevillea was reportedly used in tea and coffee plantations in Kenya partly because its much divided "feathery" leaf structure ameliorated the adverse effects of direct sunlight without casting intense shade (Woods of the World, 1996). The present chapter considers the capture and utilisation of light by grevillea and the more shade tolerant C3 crop species, cowpea, during the 1992/3 and 1993/4 short rains. The theory of the capture and utilisation of light in agroforestry systems was described in Section 1.4 and the experimental methods and analyses employed were presented in Section 4.6.

6.2 LIGHT CAPTURE AND UTILISATION DURING THE 1992/3 SHORT RAINS

Fractional interception

Figure 6.1 shows fractional interception of photosynthetically active radiation (PAR) by cowpea and grevillea (Cf_p and Tf_p respectively) throughout the season; Tf_p is represented by the regression lines of best fit in order to illustrate the seasonal trend (Section 4.6, Eq. 4.16 and Fig. 4.14).

Fractional interception of PAR by an understorey crop may be defined in two ways, firstly as fractional interception of total incoming PAR (i.e. as measured above the upperstorey trees or crop), or secondly as the fraction of the PAR incident on the crop itself that is intercepted (i.e. as a proportion of PAR transmitted by the upperstorey trees or crop). It is important to draw a distinction between these two quantities, which will henceforth be referred to as Cf_p and Cf_{pi}. Cf_{pi} did not differ significantly from the Cf_p value for sole cowpea (p from paired t-test > 0.05). However, the Cf_p value for CTd cowpea was significantly different from that of sole cowpea (p from paired t-test < 0.01), largely due to the fraction of PAR intercepted by the CTd grevillea. The seasonal mean Cf_p values for the crops greatly exceeded those for the trees, with values of 0.31 and 0.28 being recorded for Cg and CTd cowpea as compared to 0.11 and 0.04 for Td and CTd grevillea. Maximum Cf_p values did not coincide with the peak leaf area index, but occurred 1 - 2 weeks later (Figs. 6.1 and 6.2), possibly due to a combination of self-shading at the time of maximum LAI and a progressive increase in the thickness of leaves persisting in the canopy which would have led to a higher PAR absorbency.

Cumulative interception of radiation and conversion to dry matter

Cumulative PAR interception by cowpea and grevillea is shown in Figure 6.3. The crops exceeded the cumulative interception achieved by the trees within four weeks of sowing and proceeded to achieve much higher totals. Total interception by the CTd trees and crops was slightly greater than that achieved by the sole crop. Seasonal conversion coefficients (dry matter produced per unit intercepted radiation, e_p) were greater for trees than for crops (Table 6.1). However, conversion coefficients for the crop from

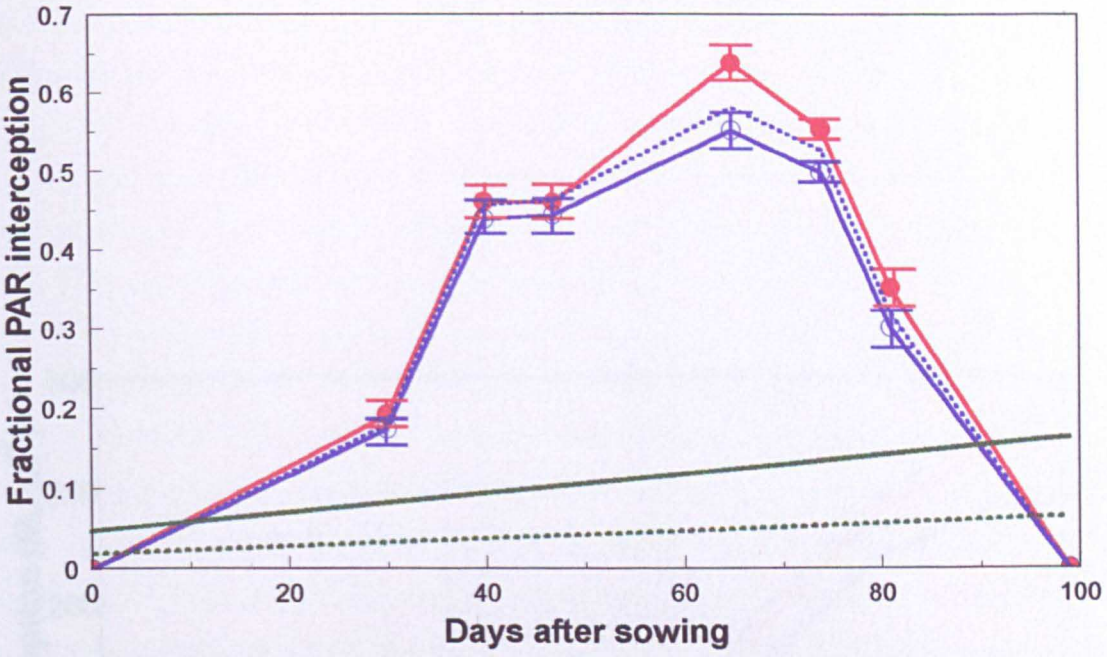


Figure 6.1 Fractional interception of incoming photosynthetically active radiation (fp) by sole (●) and CTd cowpea (o), and by the grevillea trees in the CTd (dotted green line) and Td (solid green line) treatments during the short rains 1992/3. fp for grevillea is represented by the regression lines of best fit (cf. Section 4.6, Fig. 4.14). The dotted blue line represents the fraction of the PAR transmitted by the grevillea that was intercepted by the CTd cowpea. Vertical bars represent double standard errors of the means.

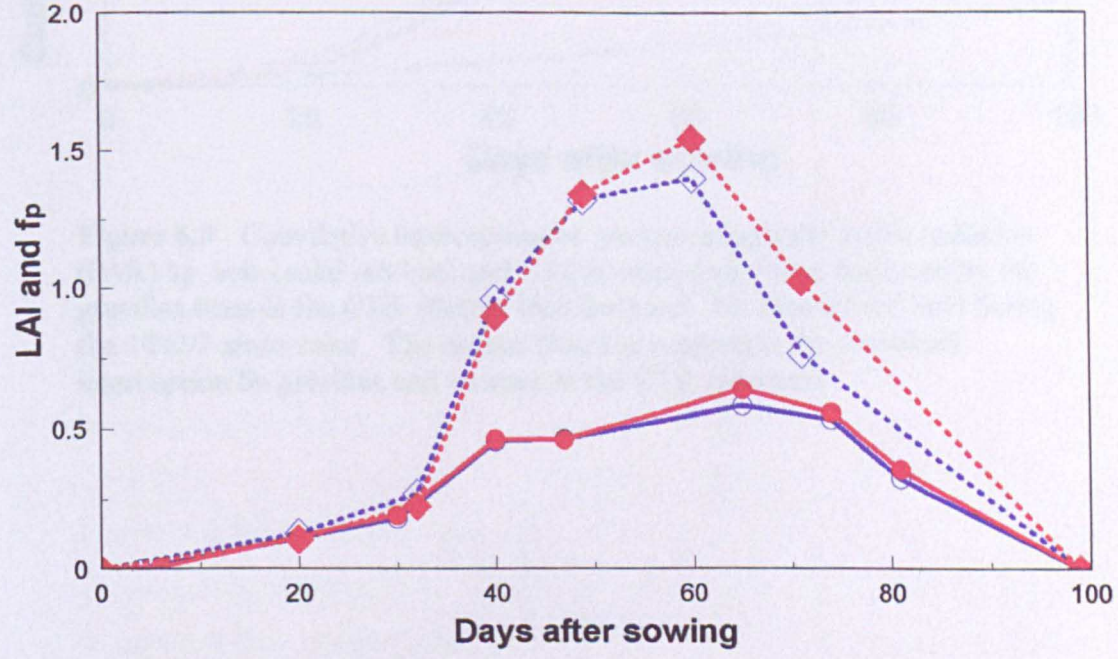


Figure 6.2 Fractional interception of incoming photosynthetically active radiation (fp , solid lines) by sole (●) and CTd cowpea (o), and leaf area index (LAI, dotted lines) for the sole (◆) and CTd cowpea (◇) during the short rains 1992/3. Standard errors are omitted for clarity and are presented in Figure 6.1 for fp and Figure 5.7 for LAI.

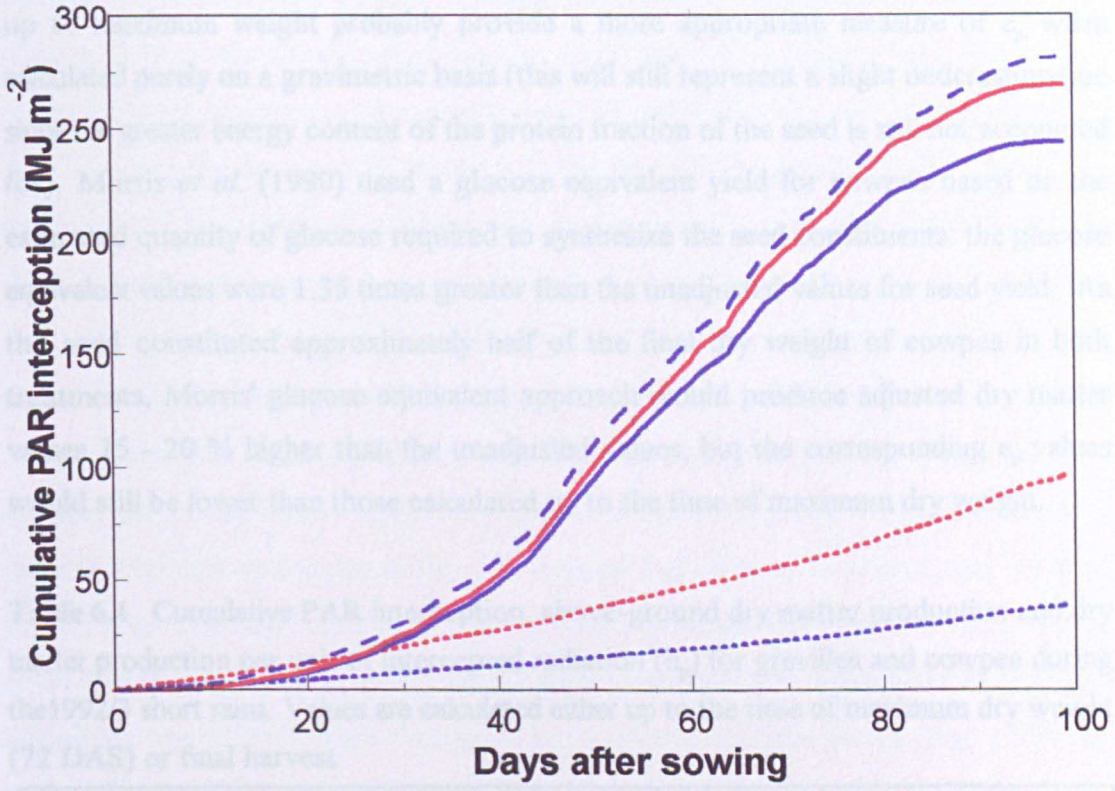


Figure 6.3 Cumulative interception of photosynthetically active radiation (PAR) by sole (solid red line) and CTd cowpea (solid blue line), and by the grevillea trees in the CTd (dotted blue line) and Td (dotted red line) during the 1992/3 short rains. The dashed blue line represents the combined interception by grevillea and cowpea in the CTd treatment.

sowing to the time of maximum weight (approximately 72 DAS) were greater than the total seasonal values for the trees. Cowpea seeds have been reported to contain 23-30 % protein (Bressani, 1985), and have a correspondingly higher energy content per unit dry weight than either the leaves or stems, which contain a greater proportion of carbohydrates. The lower e_p values recorded for cowpea at final harvest are partly because the greater energy content of the seeds resulted in an underestimation of the true radiation use efficiency (Squire, 1990). Therefore the values calculated over the period up to maximum weight probably provide a more appropriate measure of e_p when calculated purely on a gravimetric basis (this will still represent a slight underestimation since the greater energy content of the protein fraction of the seed is still not accounted for). Morris *et al.* (1990) used a glucose equivalent yield for cowpea based on the estimated quantity of glucose required to synthesize the seed constituents: the glucose equivalent values were 1.35 times greater than the unadjusted values for seed yield. As the seed constituted approximately half of the final dry weight of cowpea in both treatments, Morris' glucose equivalent approach would produce adjusted dry matter values 15 - 20 % higher than the unadjusted values, but the corresponding e_p values would still be lower than those calculated up to the time of maximum dry weight.

Table 6.1 Cumulative PAR interception, above-ground dry matter production and dry matter production per unit of intercepted radiation (e_p) for grevillea and cowpea during the1992/3 short rains. Values are calculated either up to the time of maximum dry weight (72 DAS) or final harvest.

	Grevillea		Cowpea	
	Td	CTd	Cg	CTd
Cumulative PAR interception by final harvest (MJ m^{-2})	93.9	37.7	268.9	243.5
Dry matter at final harvest (t ha^{-1})	0.76	0.28	1.43	1.56
e_p (g MJ^{-1})	0.82	0.73	0.53	0.64
Cumulative PAR interception by maximum weight (MJ m^{-2})	-	-	198.6	182.3
Dry matter at max. weight (t ha^{-1})	-	-	1.71	1.69
e_p (g MJ^{-1})	-	-	0.86	0.93

NB. Data for grevillea represent dry matter production between sowing and final harvest.

6.3 LIGHT CAPTURE AND UTILISATION DURING THE 1993/4 SHORT RAINS

Fractional interception

Figure 6.4 shows fractional interception of PAR by cowpea and grevillea (Cf_p and Tf_p) throughout the 1993/4 short rains. The seasonal mean values of Cf_p and Cf_{pi} for CTd cowpea (0.10 and 0.15) differed significantly from the corresponding value for sole cowpea (0.19, p values from paired t-tests < 0.001 and <0.01 respectively). In contrast to the previous short rains, the seasonal mean Tf_p values for the trees greatly exceeded the Cf_p values for the crops (0.28 and 0.31 for Td and CTd grevillea). Once again, the maximum Cf_p value did not coincide with maximum leaf area index in either treatment (Fig. 6.5), but on this occasion occurred approximately two weeks before the maximum LAI. This season was much drier than the previous short rains (281 versus 766 mm) and the crop exhibited heliophobic behaviour during the latter half of the season, with the leaves displaying a near-vertical posture through the midday period (Fig. 6.6). It is possible that the Cf_p values, which were measured at midday, somewhat underestimated the true PAR interception due to this near-vertical leaf posture. However, over 50 % of the total incident daily solar radiation was received within two hours on either side of noon (close to the time when Cf_p values were measured) and pronounced heliophobic behaviour was only observed during the last 3 - 4 weeks of the season (Fig. 4.15); any underestimate of Cf_p should therefore have been modest.

Cumulative interception of radiation and conversion to dry matter

Cumulative PAR interception by cowpea and grevillea is shown in Figure 6.7. Unlike the previous short rains, the crops never exceeded the cumulative interception achieved by the trees. Total cumulative interception by the CTd cowpea was only slightly over 50 % of that in the sole crop. However, total system interception by the CTd trees and crops was > 40 % greater than that for the sole trees and more than twice that for the sole crop.

As in the previous short rains, the seasonal conversion coefficients were greater for grevillea than for cowpea (Table 6.2). However, the e_p values for the crops from sowing

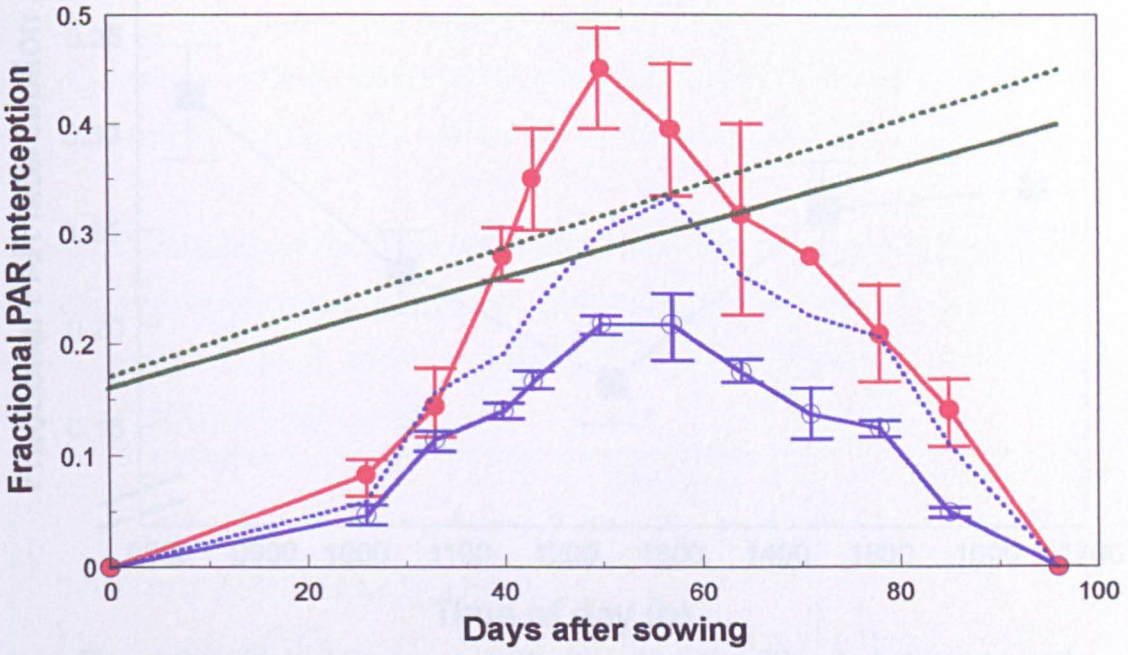


Figure 6.4 Fractional interception of incoming photosynthetically active radiation (fp) by sole (●) and CTd cowpea (o), and by the grevillea trees in the CTd (dotted green line) and Td (solid green line) treatments during the short rains 1993/4. fp for grevillea is represented by the regression lines of best fit (cf. Section 4.6, Fig. 4.14). The dotted blue line represents the fraction of the PAR transmitted by the grevillea that was intercepted by the CTd cowpea. Vertical bars represent double standard errors of the means.

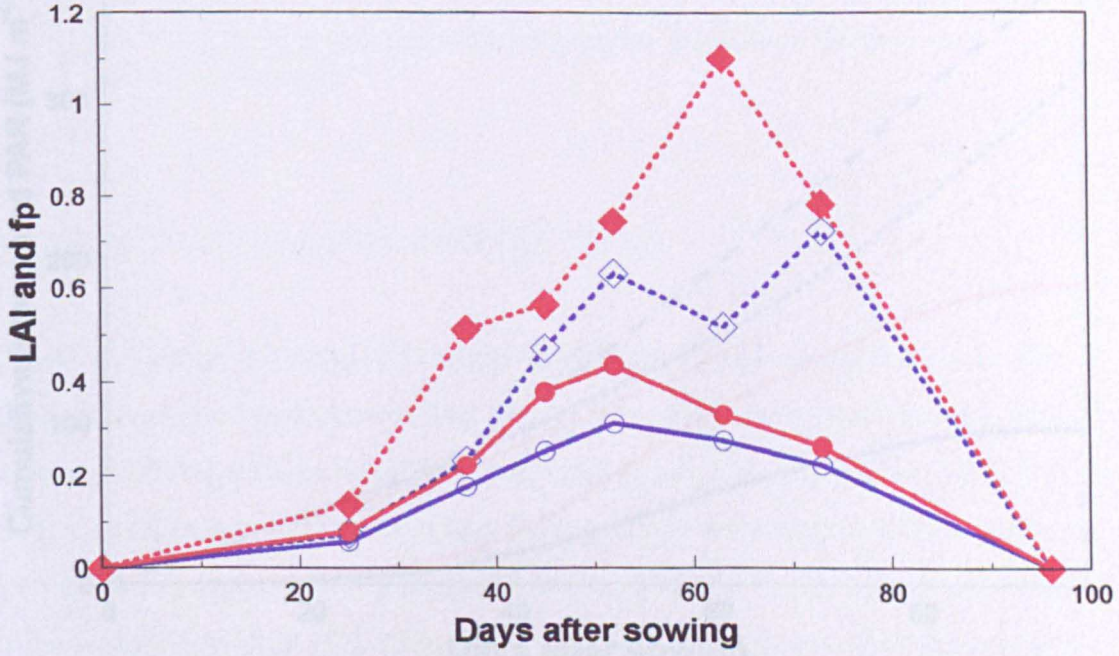


Figure 6.5 Fractional interception of incoming photosynthetically active radiation (fp , solid lines) by sole (●) and CTd cowpea (o), and leaf area index (LAI, dotted lines) for the sole (◆) and CTd cowpea (◇) during the short rains 1993/4. Standard errors are omitted for clarity and are represented in Figure 6.4 for fp and Figure 5.9 for LAI.

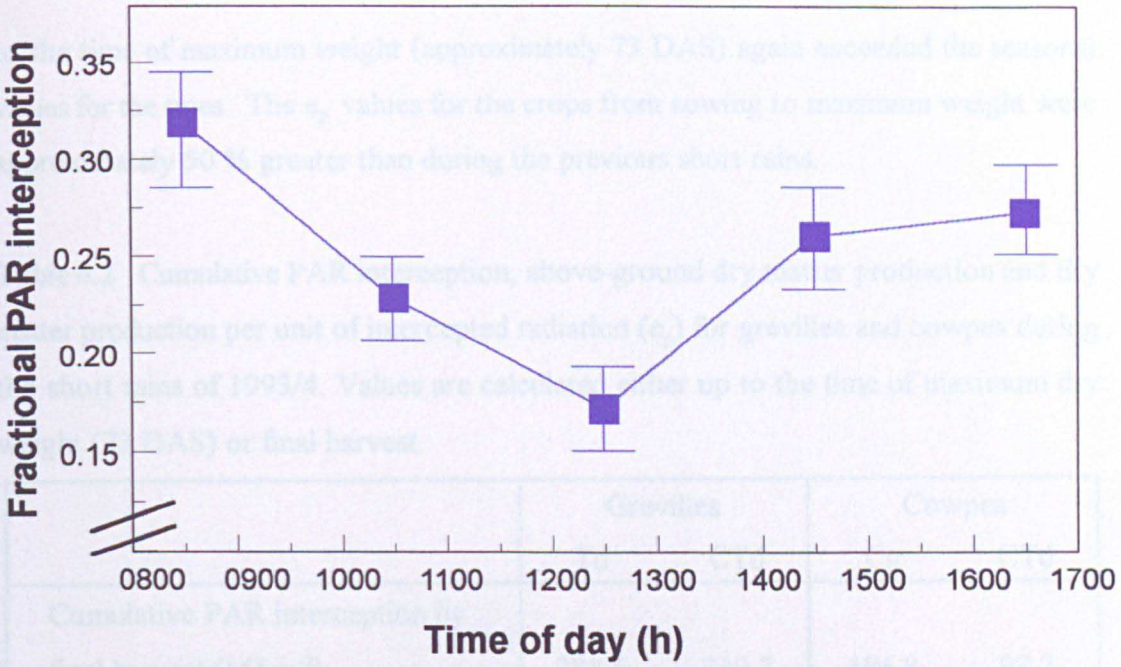


Figure 6.6 Diurnal timecourse of fractional interception of photosynthetically active radiation by cowpea in the sole crop at 78 days after sowing (18 days before harvest) during the 1993/4 short rains. The plants displayed apparent heliophobic behaviour, with near-vertical leaf positions being exhibited throughout the midday period. Vertical bars represent double standard errors of the means.

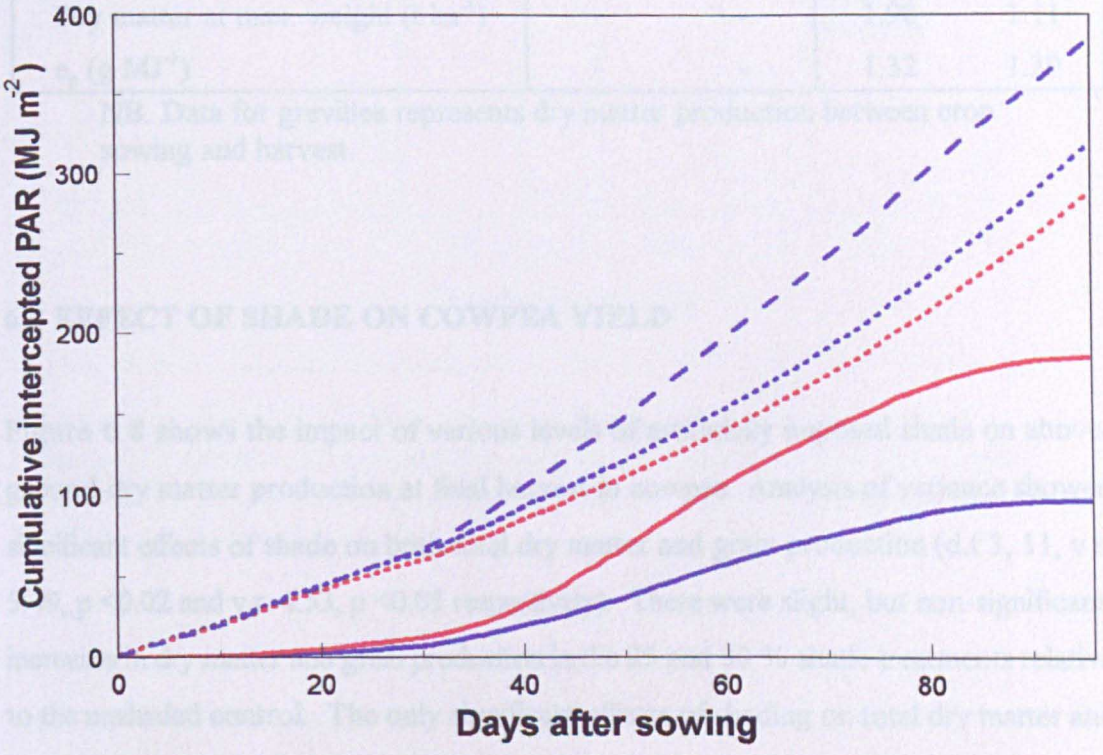


Figure 6.7 Cumulative interception of photosynthetically active radiation (PAR) by sole (solid red line) and CTd cowpea (solid blue line), and by the grevillea trees in the CTd (dotted blue line) and Td (dotted red line) during the 1993/4 short rains. The dashed blue line represents the combined interception of grevillea and cowpea in the CTd treatment.

to the time of maximum weight (approximately 73 DAS) again exceeded the seasonal values for the trees. The e_p values for the crops from sowing to maximum weight were approximately 50 % greater than during the previous short rains.

Table 6.2 Cumulative PAR interception, above-ground dry matter production and dry matter production per unit of intercepted radiation (e_p) for grevillea and cowpea during the short rains of 1993/4. Values are calculated either up to the time of maximum dry weight (73 DAS) or final harvest.

	Grevillea		Cowpea	
	Td	CTd	Cg	CTd
Cumulative PAR interception by final harvest (MJ m^{-2})	288.6	319.7	186.8	97.7
Dry matter at final harvest (t ha^{-1})	282.3	263.4	1.48	0.64
e_p (g MJ^{-1})	0.98	0.82	0.79	0.65
Cumulative PAR interception by maximum weight (MJ m^{-2})	-	-	149.9	80.0
Dry matter at max. weight (t ha^{-1})	-	-	1.98	1.11
e_p (g MJ^{-1})	-	-	1.32	1.39

NB. Data for grevillea represents dry matter production between crop sowing and harvest.

6.4 EFFECT OF SHADE ON COWPEA YIELD

Figure 6.8 shows the impact of various levels of artificially imposed shade on above-ground dry matter production at final harvest in cowpea. Analysis of variance showed significant effects of shade on both total dry matter and grain production (d.f 3, 11, v.r. 5.49, $p < 0.02$ and v.r. 4.53, $p < 0.05$ respectively). There were slight, but non-significant, increases in dry matter and grain production in the 25 and 50 % shade treatments relative to the unshaded control. The only significant effects of shading on total dry matter and grain production were observed in the 75 % shade treatment, in which production was reduced to approximately 50 % of that at the lower shade levels. Leaf size increased

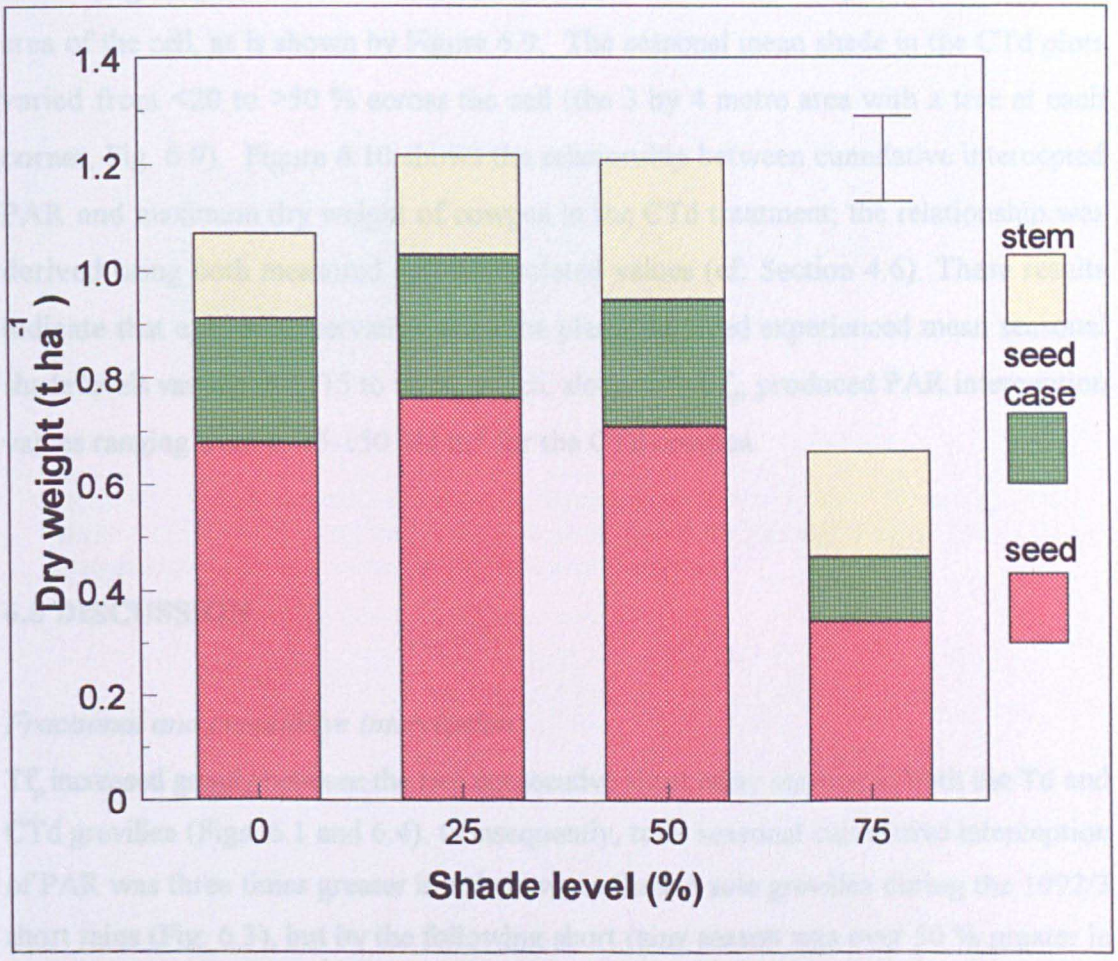


Figure 6.8 The relationship between artificially imposed shade level and above-ground dry matter production by cowpea during the 1993/4 short rains. The vertical bar represents the double standard error of the difference between the means for total dry weight.

with the increasing shade and the leaves became darker in colour but, due to the small sample area available, destructive growth analyses could not be carried out until final harvest; it was therefore impossible to quantify these effects.

In the CTd treatment, the average shade level had not reached 50 % by the end of the season (Fig. 6.4) and the mean seasonal Tf_p exceeded this value only in a small localised area of the cell, as is shown by Figure 6.9. The seasonal mean shade in the CTd plots varied from <20 to >50 % across the cell (the 3 by 4 metre area with a tree at each corner, Fig. 6.9). Figure 6.10 shows the relationship between cumulative intercepted PAR and maximum dry weight of cowpea in the CTd treatment; the relationship was derived using both measured and interpolated values (cf. Section 4.6). These results indicate that e_p was conservative since the plants involved experienced mean seasonal shade levels varying from 15 to 56 %, which, along with Cf_p, produced PAR interception values ranging from c. 45-150 MJ m^{-2} for the CTd cowpea.

6.5 DISCUSSION

Fractional and cumulative interception

Tf_p increased greatly between the two consecutive short rainy seasons in both the Td and CTd grevillea (Figs. 6.1 and 6.4). Consequently, total seasonal cumulative interception of PAR was three times greater in sole cowpea than in sole grevillea during the 1992/3 short rains (Fig. 6.3), but by the following short rainy season was over 50 % greater in the sole grevillea than in the sole cowpea (Fig. 6.7). The cumulative interception of PAR for the CTd grevillea and cowpea combined was only slightly greater than the sole crop during the 1992/3 short rains, but was more than twice that of the sole cowpea and over 40 % greater than that of the sole grevillea during the 1993/4 short rains. The CTd cowpea intercepted 50 % as much PAR as the sole cowpea and the greater combined interception by the trees and crops in the CTd system arose largely due to the high Tf_p value for the CTd grevillea which was 10 % greater than that for the Td grevillea. This increase in interception by the CTd system during the 1993/4 short rains is similar to the *Senna spectabilis*/cowpea system described by Ong *et al.* (1996; Fig. 1.9), and illustrates

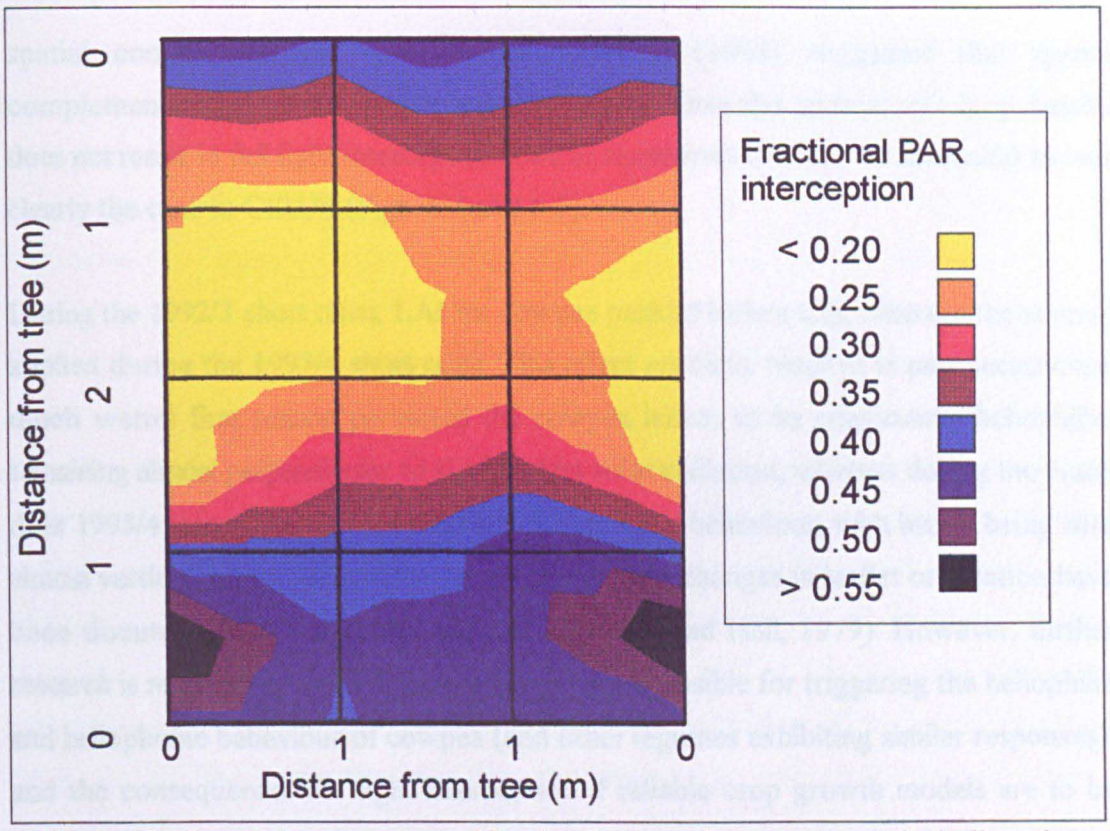


Figure 6.9 Seasonal mean pattern of fractional interception of photosynthetically active radiation (PAR) by the grevillea in the CTd treatment during the short rains 1993/4. The rectangle represents a 3 x 4 m cell with a tree at each corner.

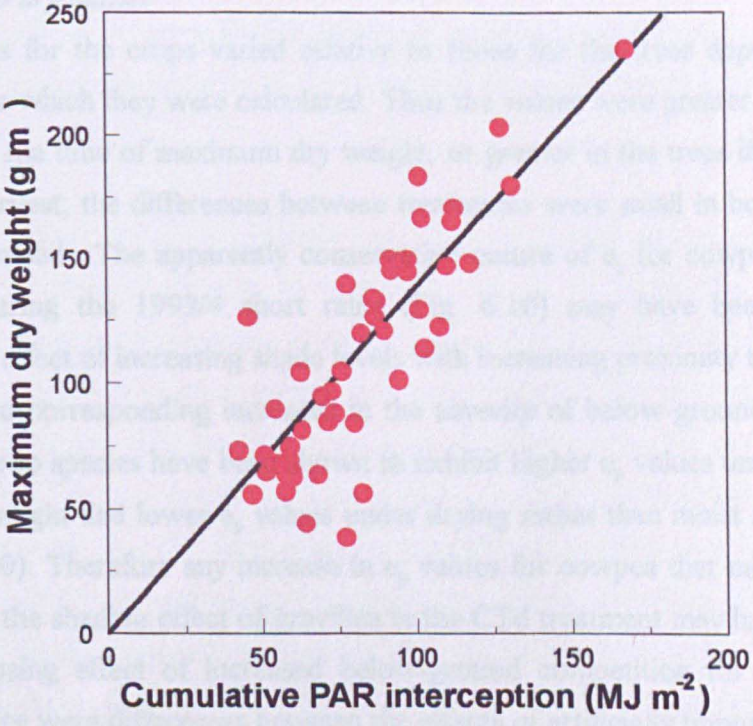


Figure 6.10 The relationship between cumulative intercepted photosynthetically active radiation and above-ground dry matter production for cowpea at the time of maximum dry weight (73 days after sowing) in the CTd treatment during the 1993/4 short rains. The symbols represent the interpolated values for the 9 by 7 grid (see text) and the regression line has the equation $y = 1.395\ x$ ($r^2 = 0.75$, $p < 0.001$, s.e of coefficient = 0.035).

spatial complementarity: Keating and Carberry (1993) suggested that spatial complementarity for light capture is probable only when the optimal sole crop density does not result in full light interception (due to limitations of water or nutrients) as was clearly the case in CIRUS (Figs. 6.4 and 6.5).

During the 1992/3 short rains, LAI for cowpea peaked before Cfp, whereas the reverse applied during the 1993/4 short rains. This effect probably resulted in part because the much wetter first season permitted the cowpea leaves to be consistently heliophilic, remaining almost perpendicular to the incident solar radiation, whereas during the much drier 1993/4 season the cowpea exhibited heliophobic behaviour, with leaves being held almost vertical during the midday period. Reversible changes in leaflet orientation have been documented as a drought response (Shackel and Hall, 1979). However, further research is required to establish the mechanisms responsible for triggering the heliophilic and heliophobic behaviour of cowpea (and other legumes exhibiting similar responses), and the consequences for light interception if reliable crop growth models are to be developed.

Conversion to dry matter

The e_p values for the crops varied relative to those for the trees depending on the timescale over which they were calculated. Thus the values were greater in the crops if calculated to the time of maximum dry weight, or greater in the trees if calculated up until final harvest; the differences between treatments were small in both short rainy seasons examined. The apparently conservative nature of e_p for cowpea in the CTd treatment during the 1993/4 short rains (Fig. 6.10) may have been due to the confounding effect of increasing shade levels with increasing proximity to the grevillea (Fig. 6.9) and corresponding increases in the severity of below-ground competition. Several C3 crop species have been shown to exhibit higher e_p values under shade than under full sunlight and lower e_p values under drying rather than moist soil conditions (Squire, 1990). Therefore any increase in e_p values for cowpea that might have been produced by the shading effect of grevillea in the CTd treatment may have been offset by the opposing effect of increased below-ground competition for soil moisture. Although there were differences between the effects of artificially imposed and natural tree shade, the artificial shade trial showed that there was no reduction in total above-ground dry matter production until a 75 % shade level was imposed. This confirms the

statement of Monteith *et al.* (1991) that experiments in the semi-arid tropics have shown little impact of shade levels of up to 50 % on the yield of legumes. These results suggest that, given sufficient rainfall to eliminate below-ground competition for moisture, the yields of intercropped cowpea grown under a grevillea canopy of similar size to the CTd trees during the 1993/4 short rains might have matched those of the sole crop.

Shade produced morphological changes in the artificial shade trial, with leaf size increasing and leaf colour darkening as the intensity of shading increased (cf. Plates 6.1 and 6.2); these morphological changes were not observed under the natural tree shade in the CTd plots. It is possible that the cowpea was unable to compensate for the increase in shading intensity in the CTd plots as the tree canopy grew larger, by increasing its leaf expansion and darkening their colour, because of below-ground competition for soil-moisture. Machakos, at an altitude of over 1600 m with its frequent clear skies, is a light-rich (euphotic) site with solar radiation frequently exceeding 20 MJ m^{-2} day^{-1} during the short rains. The results from this trial suggest that light was not the primary limiting resource for either trees or crops, even for the intercropped cowpea under the well established tree canopy of the 1993/4 short rains. Further research is required to establish the processes that permit cowpea to maintain its yield under conditions of up to 50 % shade. However, given that Machakos is a euphotic environment, reductions in cowpea yield are likely to occur at lower shade levels in environments with lower levels of incident solar radiation.

Wainwright (1995) found that an understorey crop of amaranth (*Amaranthus cruentus*) suffered no significant reduction in biomass at up to 42 % shading intensity and suggested that planting arrangements could be designed so that understorey crops could be "fitted" into the niches created by trees. It is possible that simple innovative cultivation practices may enhance yields by utilising mixtures of shade tolerant C3 crop species with upperstorey trees. Shade tolerance is common in woodland legumes (Muir and Pitman, 1989) and research into the mechanisms that confer this tolerance may be helpful in determining desirable characteristics for understorey crops. However, the tolerance of cowpea to artificially imposed shade levels of up to 50 % suggests that light was not a major limiting factor and below-ground competition for water was more important in reducing yield in the agroforestry treatments. The implications of light capture and utilisation and the importance of shade for the design of agroforestry systems are discussed further in Chapter 8.

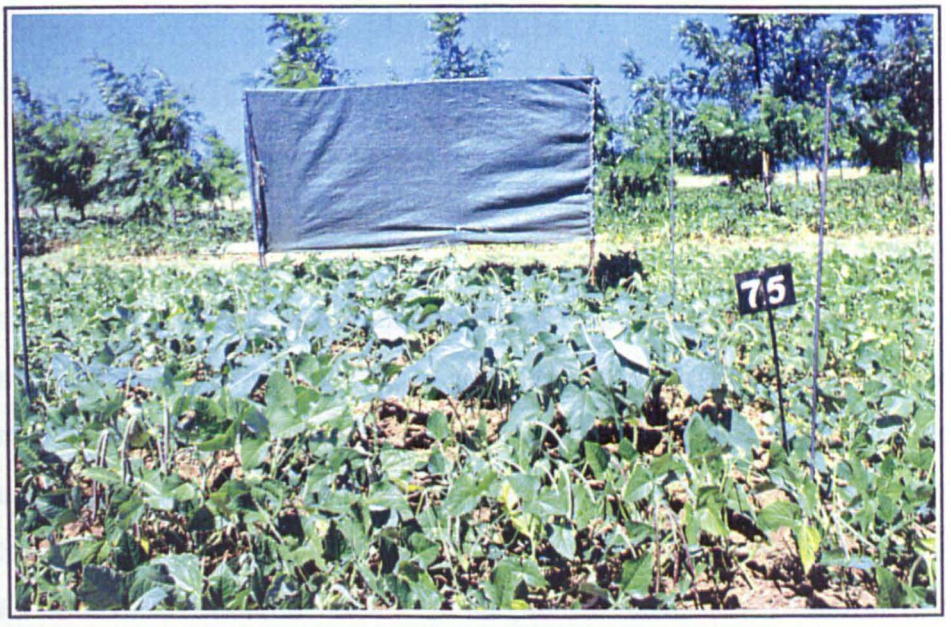


Plate 6.1 A 75 % shade net temporarily repositioned for the photograph in the sole cowpea treatment of CIRUS during the 1993/4 short rains (c. 60 days after sowing). The cowpea subjected to the 75 % shade were between the net and the flag.

Plate 6.2 Cowpea subjected to the 75 % shade with the shade net temporarily removed for the photograph in the sole cowpea treatment of CIRUS during the 1993/4 short rains (c. 60 days after sowing). A leaf from a cowpea plant grown in the surrounding unshaded plot was removed and held adjacent to the larger leaves that had been grown under shade for comparison.

CHAPTER 7

WATER BUDGET INCLUDING TRANSPIRATION AND WATER UTILISATION BY THE TREES AND CROPS

7.1 INTRODUCTION

The partitioning of water between trees and crops in agroforestry systems in the semi-arid tropics is of vital importance as this is frequently the key factor determining the viability of the system. The capture and utilisation of water in agroforestry systems have already been shown to have a major impact on the relative yields of the trees and crops: for example, it was shown in Chapter 3 that maize yield was reduced by 30 % when intercropped with leucaena due to competition for water from the predominantly shallow rooted trees.

Significant yield reductions when cowpea was intercropped with grevillea during the 1993/4 short rains were reported in Chapter 5, and in Chapter 6 these were shown to be attributable to effects other than shade from the trees. The present chapter considers the water balance of the grevillea-based agroforestry system during the 1992/3 short rains, when rainfall was more than double the seasonal average at 766 mm, the 1993/4 short rains when rainfall was 20 % below average at 280.5 mm, and (due to the failure of the 1993 long rains) the intervening eight month long dry season, during which 124 mm of rain was received. This chapter includes studies of water capture and utilisation by the grevillea trees, an attempt to quantify the degree of below-ground complementarity in water use between grevillea and cowpea, estimates of water use by cowpea, soil evaporation and run-off, and a discussion of rainfall interception losses.

7.2 TRANSPIRATION BY GREVILLEA

In order to estimate transpiration by grevillea as accurately as possible, attempts were made to select representative trees for sap flux measurements, with larger than average, average

and smaller than average trees being included within each group of trees examined. However, due to the limitations on maximum cable length between the datalogger and the heat balance gauges because of potential voltage losses, it was not always possible to select trees that were fully representative of the average tree size for specific treatments. At any given point in time, total water use may be expected to be proportional to the cross-sectional area of the stem: Figure 7.1 confirms that this was the case since the relationship between total daily transpiration and the square of basal diameter (BD^2) was consistently linear from the time measurements commenced in November 1992 until they ended in February 1994. The basal diameters of the trees were recorded whenever the sap flux gauges were moved. The transpiration values obtained were multiplied by the ratio of the treatment mean BD^2 to the corresponding BD^2 value for the sampled trees to correct for any over or under-estimate in transpiration resulting from bias in the tree sizes selected for measurement. The transpiration values presented here are the means for three trees, corrected for stem size where necessary (when DBH exceeded 32 mm using equations 4.16 and 4.17) and for bias in tree size (using the ratio of the treatment mean BD^2 to the BD^2 of the trees sampled).

Daily transpiration values exhibited marked day-to-day variation within specific treatments (Figs. 7.2 a and b). Jones (1992) stated that net radiation is the dominant component of the energy balance of a plant leaf or canopy and is responsible for driving many of the other energy components. Global radiation varied from 10 - 25 MJ m^{-2} d^{-1} and comparison of the daily total transpiration values with those for global radiation revealed that the variation in transpiration was closely correlated with that in global radiation (Figs. 7.2 a and b). Figure 7.3 shows the relationship between global radiation and transpiration, which was used to estimate transpiration between consecutive sap flux measurement periods. Similar relationships (data not shown) were used to estimate transpiration by trees in the Td and CTd treatments between successive sap flux measurement periods or when data were lost due to battery failure or penetration of rain into the heat balance gauges. In order to estimate transpiration during the four month break in measurements between mid-June and

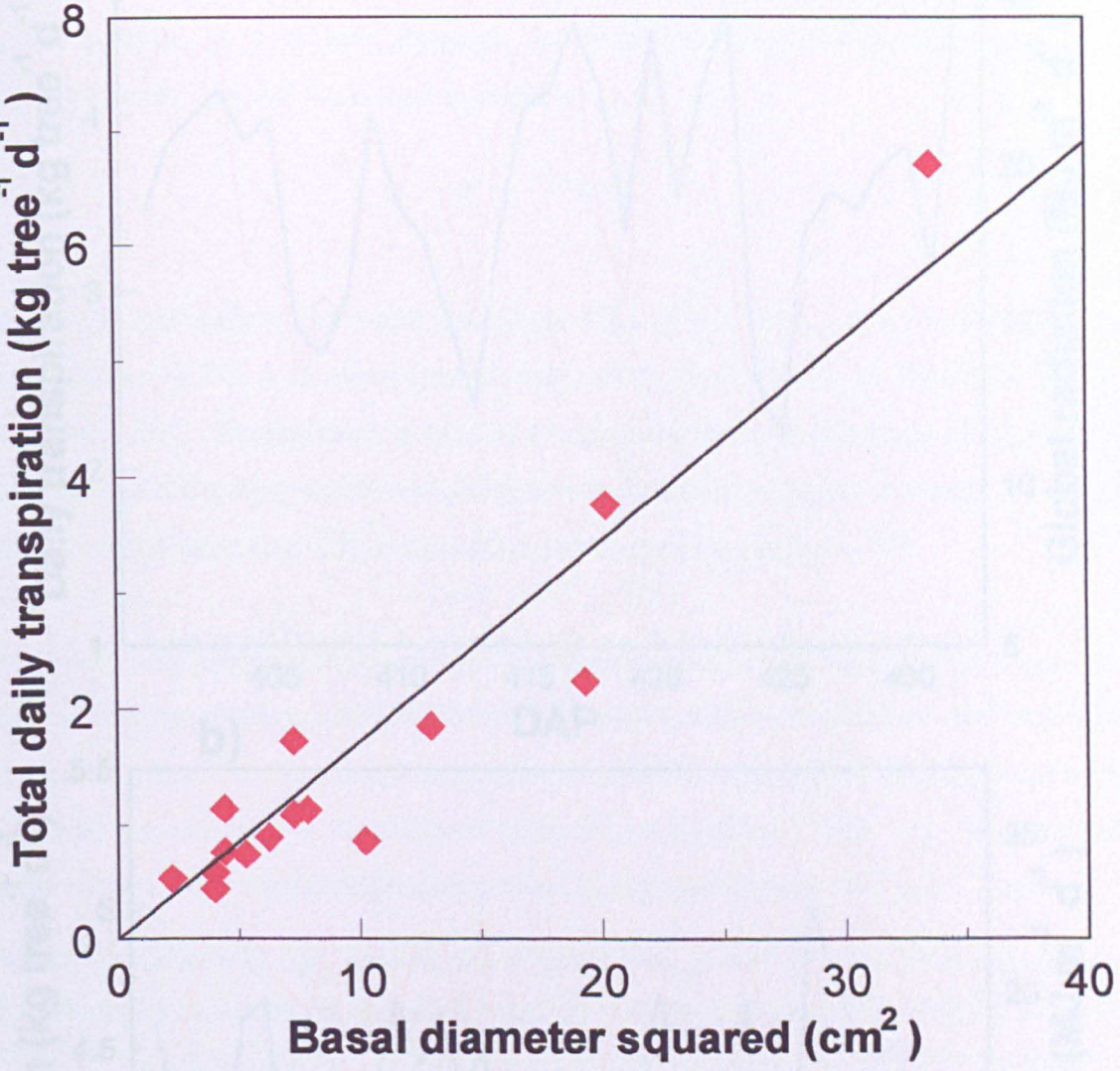


Figure 7.1 Relationship between total daily transpiration and the square of the basal diameter of grevillea trees 14 months after planting during December of the 1992/3 short rains. Values shown are for 15 trees from treatments Td, CTd and CTc of CIRUS.

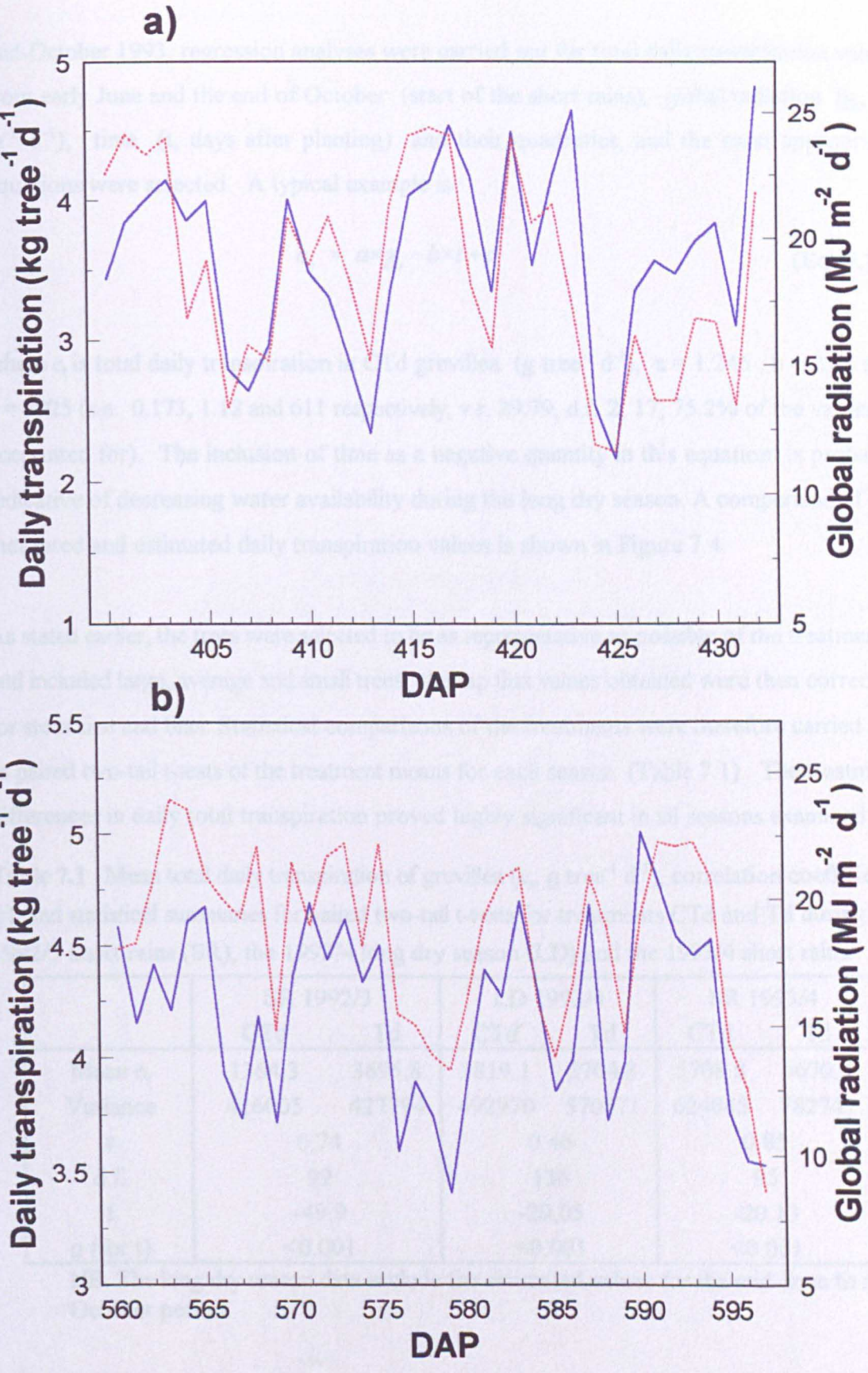


Figure 7.2 Daily timecourses for total daily global radiation (—) and total daily transpiration (—) by grevillea for (a) treatment Td during the 1992/3 short rains and (b) treatment CTd during the 1993/4 long dry season. DAP denotes days after planting.

mid-October 1993, regression analyses were carried out for total daily transpiration values from early June and the end of October (start of the short rains), global radiation (g_r, kJ m^{-2} d^{-1}), time (t, days after planting) and their quadratics, and the most appropriate equations were selected. A typical example is:

$$e_t = a \times g_r - b \times t + c \qquad \textbf{(Eq. 7.1)}$$

where e_t is total daily transpiration in CTd grevillea (g $tree^{-1}$ d^{-1}), a = 1.246 , b = 2.46 and c = 3925 (s.e. 0.173, 1.12 and 611 respectively, v.r. 29.79, d.f. 2, 17, 75.2% of the variation accounted for). The inclusion of time as a negative quantity in this equation is probably indicative of decreasing water availability during the long dry season. A comparison of the measured and estimated daily transpiration values is shown in Figure 7.4.

As stated earlier, the trees were selected to be as representative as possible of the treatments, and included large, average and small trees; the sap flux values obtained were then corrected for stem size and bias. Statistical comparisons of the treatments were therefore carried out as paired two-tail t-tests of the treatment means for each season (Table 7.1). The treatment differences in daily total transpiration proved highly significant in all seasons examined.

Table 7.1 Mean total daily transpiration of grevillea (e_t, g $tree^{-1}$ d^{-1}), correlation coefficients (r), and statistical summaries for paired two-tail t-tests for treatments CTd and Td during the 1992/3 short rains (SR), the 1993/4 long dry season (LD) and the 1993/4 short rains.

	SR 1992/3		LD 1993/4		SR 1993/4	
	CTd	Td	CTd	Td	CTd	Td
Mean e_t	1364.3	3695.8	3819.1	5704.8	5708.8	6670.4
Variance	416005	427794	492970	570571	624045	782741
r	0.74		0.46		0.85	
d.f.	99		136		95	
t	-49.9		-29.05		-20.13	
p (for t)	<0.001		<0.001		<0.001	

NB. The long dry season data exclude the estimated values for the mid-June to mid-October period.

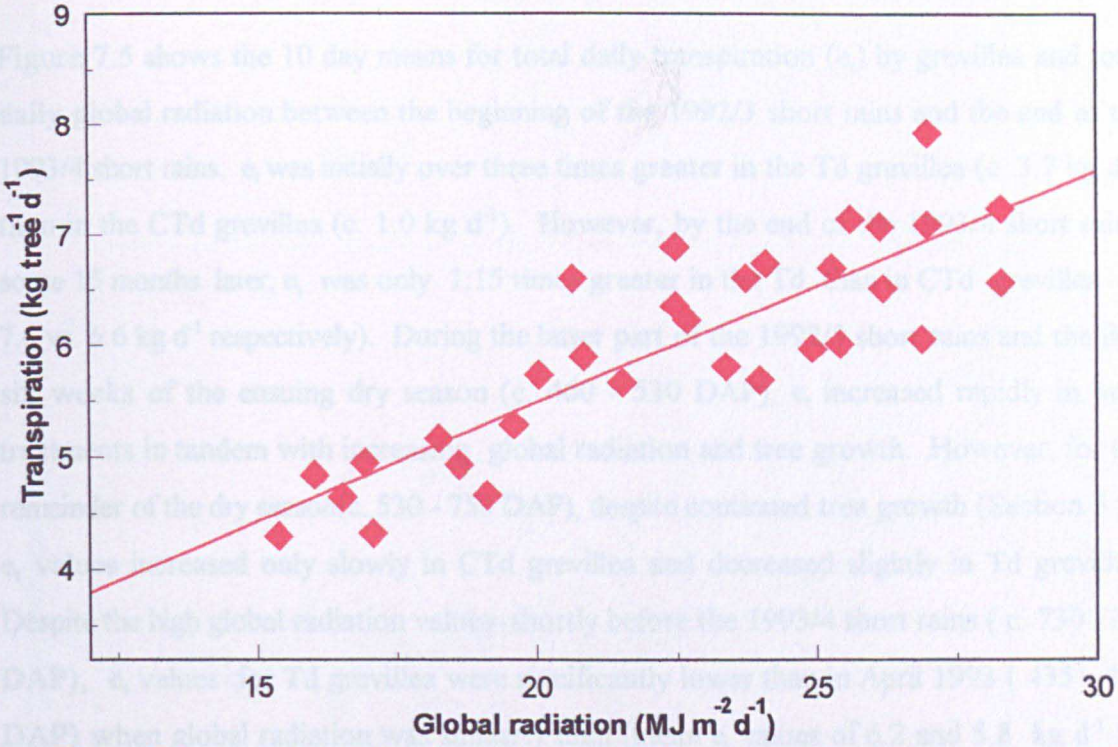


Figure 7.3 Relationship between total daily transpiration by grevillea 25-27 months after planting and total daily global radiation for treatment CTd during the 1993/4 short rains. The regression is $y = 2.1 x + 1273.1$, ($r^2 = 0.74$, $n = 31$, s.e. of parameters = 0.23 and 527.4).

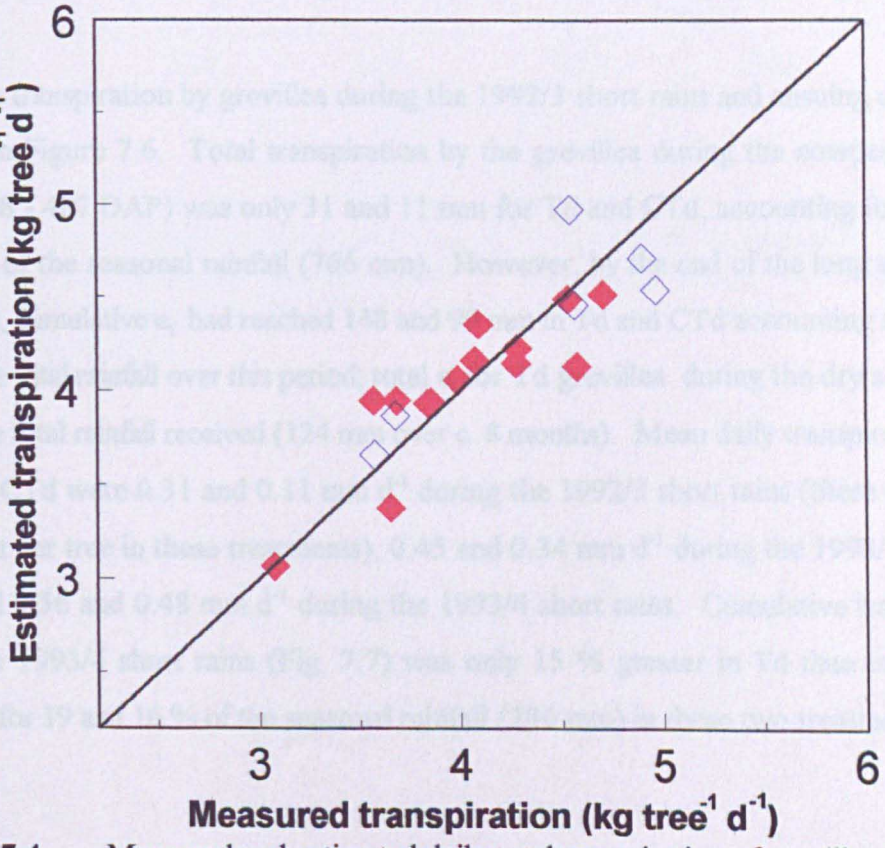


Figure 7.4 Measured and estimated daily total transpiration of grevillea in the CTd treatment during June (♦) and October (◊) of the 1993/4 long dry season. The 1:1 line is shown (see text for details of estimation).

Figure 7.5 shows the 10 day means for total daily transpiration (e_t) by grevillea and total daily global radiation between the beginning of the 1992/3 short rains and the end of the 1993/4 short rains. e_t was initially over three times greater in the Td grevillea (c. 3.7 kg d^{-1}) than in the CTd grevillea (c. 1.0 kg d^{-1}). However, by the end of the 1993/4 short rains, some 15 months later, e_t was only 1.15 times greater in the Td than in CTd grevillea (c. 7.6 vs. 6.6 kg d^{-1} respectively). During the latter part of the 1992/3 short rains and the first six weeks of the ensuing dry season (c. 460 - 530 DAP), e_t increased rapidly in both treatments in tandem with increasing global radiation and tree growth. However, for the remainder of the dry season(c. 530 - 750 DAP), despite continued tree growth (Section 5.2), e_t values increased only slowly in CTd grevillea and decreased slightly in Td grevillea. Despite the high global radiation values shortly before the 1993/4 short rains (c. 730 -748 DAP), e_t values for Td grevillea were significantly lower than in April 1993 (435 - 464 DAP) when global radiation was similarly high (mean e_t values of 6.2 and 5.8 kg d^{-1} for April 1993 and October 1993, immediately before the short rains, respectively; $t = 4.2$ from two-tailed t-test, $p < 0.0001$, 36 d.f.. NB. daily transpiration values for each period were treated as separate data sets allowing the two periods two be compared using a t-test).

Cumulative transpiration by grevillea during the 1992/3 short rains and ensuing dry season is shown in Figure 7.6. Total transpiration by the grevillea during the cowpea growing season (388 - 487 DAP) was only 31 and 11 mm for Td and CTd, accounting for only 4.0 and 1.5 % of the seasonal rainfall (766 mm). However, by the end of the long dry season (748 DAP), cumulative e_t had reached 148 and 99 mm in Td and CTd accounting for 19 and 16 % of the total rainfall over this period; total e_t for Td grevillea during the dry season was close to the total rainfall received (124 mm over c. 8 months). Mean daily transpiration rates for Td and CTd were 0.31 and 0.11 mm d^{-1} during the 1992/3 short rains (there was 12 m^2 of land area per tree in these treatments), 0.45 and 0.34 mm d^{-1} during the 1993/4 long dry season and 0.56 and 0.48 mm d^{-1} during the 1993/4 short rains. Cumulative transpiration during the 1993/4 short rains (Fig. 7.7) was only 15 % greater in Td than in CTd and accounted for 19 and 16 % of the seasonal rainfall (286 mm) in these two treatments by the

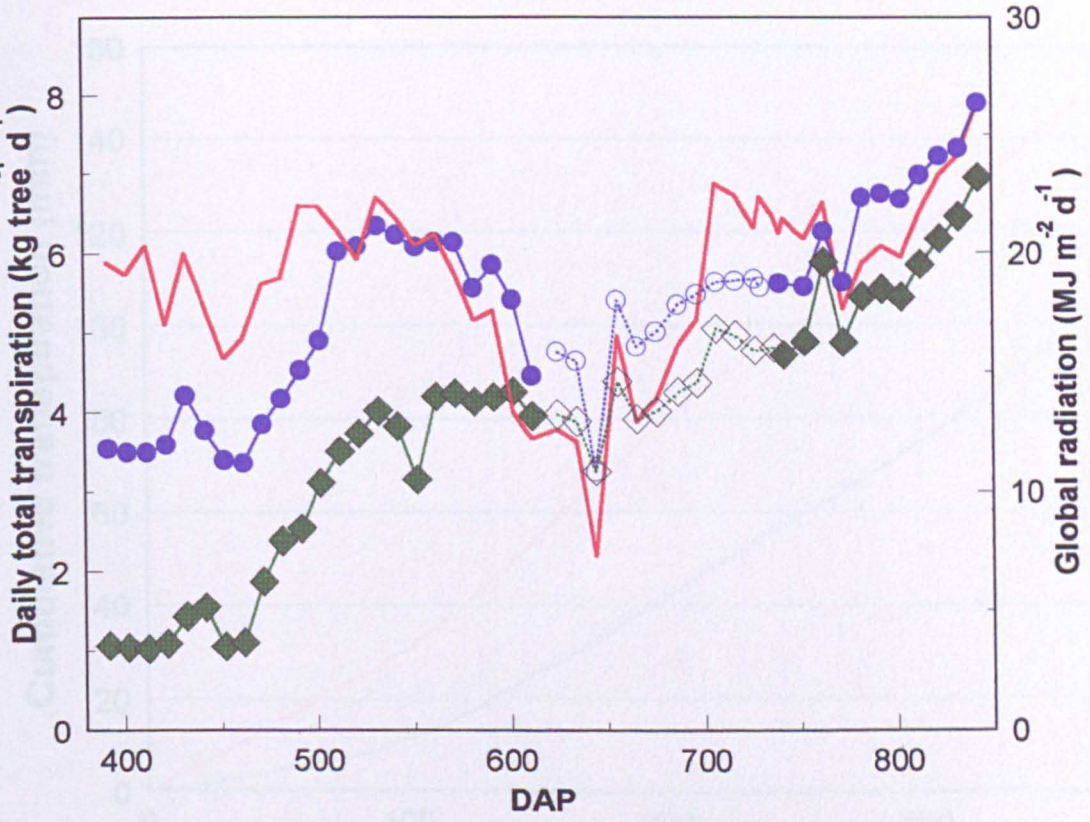


Figure 7.5 10 day means for total daily global radiation (—) and total daily transpiration by grevillea in treatments Td (●) and CTd (◆) from the beginning of the 1992/3 short rains until the end of the 1993/4 short rains season. The estimated values from the latter part of the 1993 long dry season are represented by the dotted lines and open symbols.

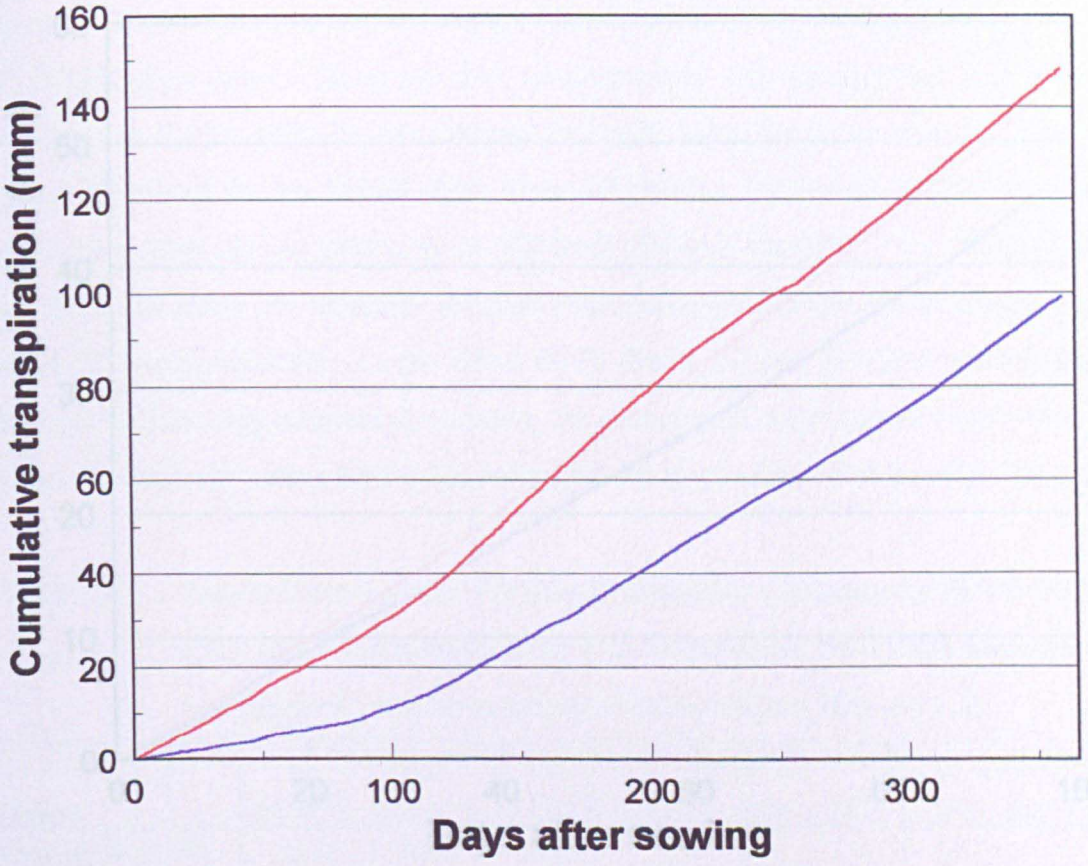


Figure 7.6 Cumulative transpiration by Td (—) and CTd (—) grevillea during the 1992/3 short rains and subsequent dry season. Data calculated from the date of sowingof cowpea (05/11/92).

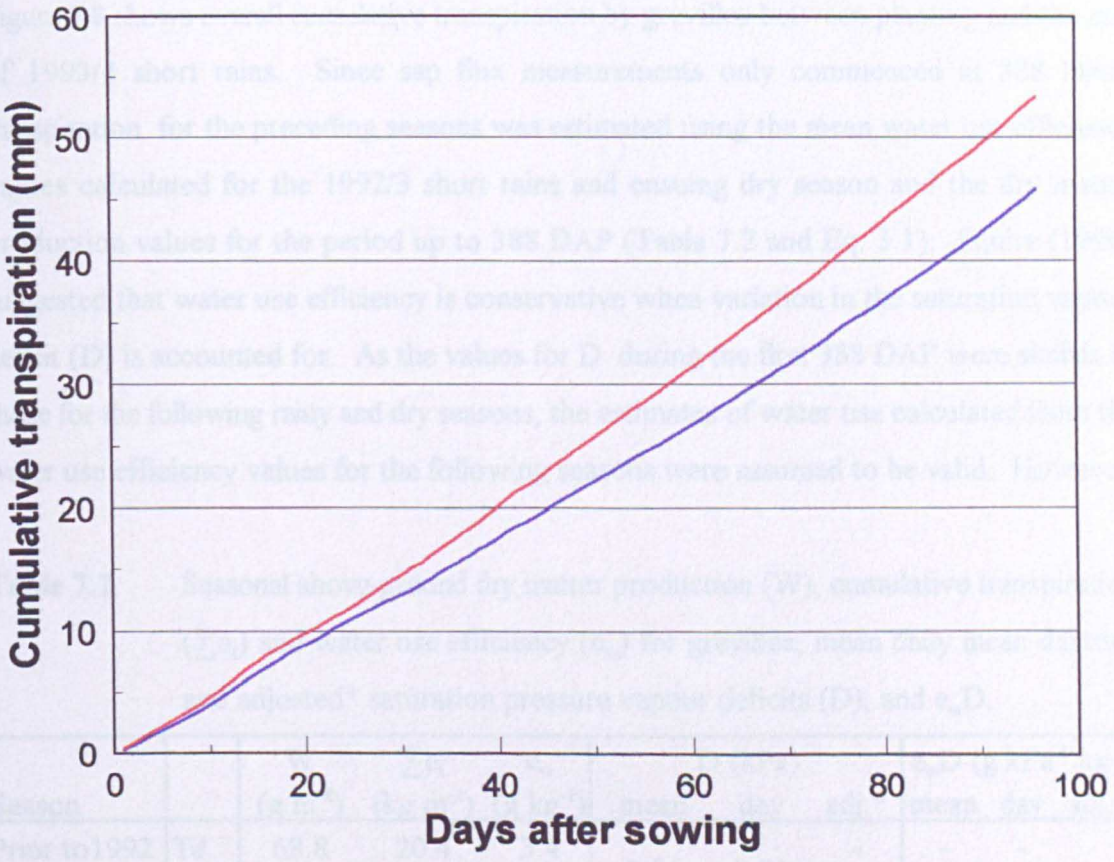


Figure 7.7 Cumulative transpiration by Td (–) and CTd (–) grevillea during the 1993/4 short rains. Data calculated from the date of sowing of cowpea (01/11/93).

time of cowpea harvest (844 DAP); although transpiration was only 15% greater in Td than in CTd during the 1993/4 short rains, the daily transpiration values for the season were still significantly different, ($t = 20.1$ from two-tailed t-test, $p < 0.0001$, 95 d.f.).

Figure 7.8 shows overall cumulative transpiration by grevillea between planting and the end of 1993/4 short rains. Since sap flux measurements only commenced at 388 DAP, transpiration for the preceding seasons was estimated using the mean water use efficiency values calculated for the 1992/3 short rains and ensuing dry season and the dry matter production values for the period up to 388 DAP (Table 7.2 and Eq. 3.1). Squire (1990) suggested that water use efficiency is conservative when variation in the saturation vapour deficit (D) is accounted for. As the values for D during the first 388 DAP were similar to those for the following rainy and dry seasons, the estimates of water use calculated from the water use efficiency values for the following seasons were assumed to be valid. However,

Table 7.2 Seasonal above-ground dry matter production (W), cumulative transpiration ($\sum e_t$) and water use efficiency (e_w) for grevillea, mean daily mean daytime and adjusted* saturation pressure vapour deficits (D), and e_wD.

Season		W ($g\ m^{-2}$)	$\sum e_t$ ($kg\ m^{-2}$)	e_w ($g\ kg^{-1}$)	D (kPa) mean	D (kPa) day	D (kPa) adj.*	e_wD ($g\ kPa^{-1}\ kg$) mean	e_wD ($g\ kPa^{-1}\ kg$) day	e_wD ($g\ kPa^{-1}\ kg$) adj.*
Prior to1992	Td	68.8	20.4	3.4	0.56	0.91	-	-	-	
Short rains**	CTd	16.7	4.7	3.6			-	-	-	-
Long dry	Td	424	117.6	3.6	0.77	1.12	1.19	2.8	4.0	4.3
1993	CTd	326.4	88.3	3.7			1.19	2.8	4.1	4.4
Short rains	Td	76.7	30.8	2.5	0.47	0.77	0.85	1.2	1.9	2.1
1992/3	CTd	28.0	11.1	2.5			0.89	1.2	1.9	2.2
Short rains	Td	282	53.4	5.3	0.72	1.02	0.95	3.8	5.4	5.0
1993/4	CTd	263	45.7	5.8			0.99	4.1	5.9	5.7

* The mean D weighted by diurnal transpiration (see text).

** The values for e_w for this period were taken as the value of e_w for the period of the short rains 1992/3 and following dry season and $\sum e_t$ values were calculated using equation 3.1 (see text).

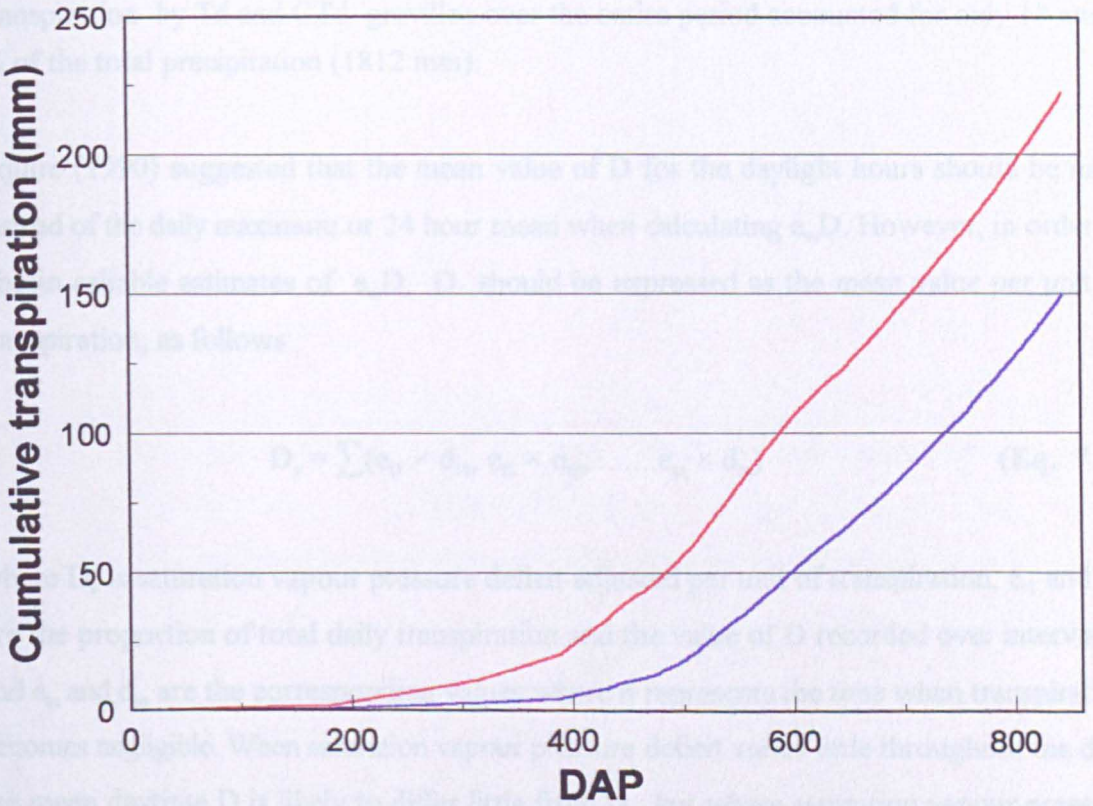


Figure 7.8 Cumulative transpiration by Td (–) and CTd (–) grevillea from planting in October 1991 to the cowpea harvest at the end of the 1993/4 short rains 27 months later. DAP denotes days after planting.

the influence of tree age on water use efficiency has been little studied and it is possible that the value for grevillea may have changed with age, but given the modest growth (and hence water use) of the saplings during the first year compared with the following year, any inaccuracy in estimating water use prior to the commencement of direct transpiration measurement would have had little impact on the total cumulative values. Cumulative transpiration by Td and CTd grevillea over the entire period accounted for only 13 and 8 % of the total precipitation (1812 mm).

Squire (1990) suggested that the mean value of D for the daylight hours should be used instead of the daily maximum or 24 hour mean when calculating e_wD. However, in order to obtain reliable estimates of e_wD, D should be expressed as the mean value per unit of transpiration, as follows:

$$D_e = \sum(e_{t1} \times d_{t1}, e_{t2} \times d_{t2}, \ldots\ldots e_{tn} \times d_{tn}) \qquad \textbf{(Eq. 7.2)}$$

where D_e is saturation vapour pressure deficit adjusted per unit of transpiration, e_{t1} and d_{t1} are the proportion of total daily transpiration and the value of D recorded over interval 1, and e_{tn} and d_{tn} are the corresponding values where n represents the time when transpiration becomes negligible. When saturation vapour pressure deficit varies little throughout the day, the mean daytime D is likely to differ little from D_e, but where saturation vapour pressure deficit changes markedly, D_e may be either greater or smaller than the mean daytime D value. Figure 7.9a shows the diurnal timecourses of transpiration in grevillea and D when the mean daytime D was low and the soil wet. In both treatments, over 60 % of the total daily transpiration (63 and 71 % for Td and CTd) occurred between 1200 and 1700 h, when the mean D was 42 % above the daytime mean. In contrast, when the mean daytime D was relatively high and the soil was dry, less than 40 % (38 and 36 % for Td and CTd) of the daily transpiration occurred during this period, and over 50 % occurred before 1200 h when mean D was less than half of the daytime mean. If equation 7.2 is applied to the data presented in Figure 7.9a, the D_e values obtained for CTd and Td are 0.78 and 0.83 kPa compared to the daytime mean of 0.64 kPa. The equivalent calculations for the data shown

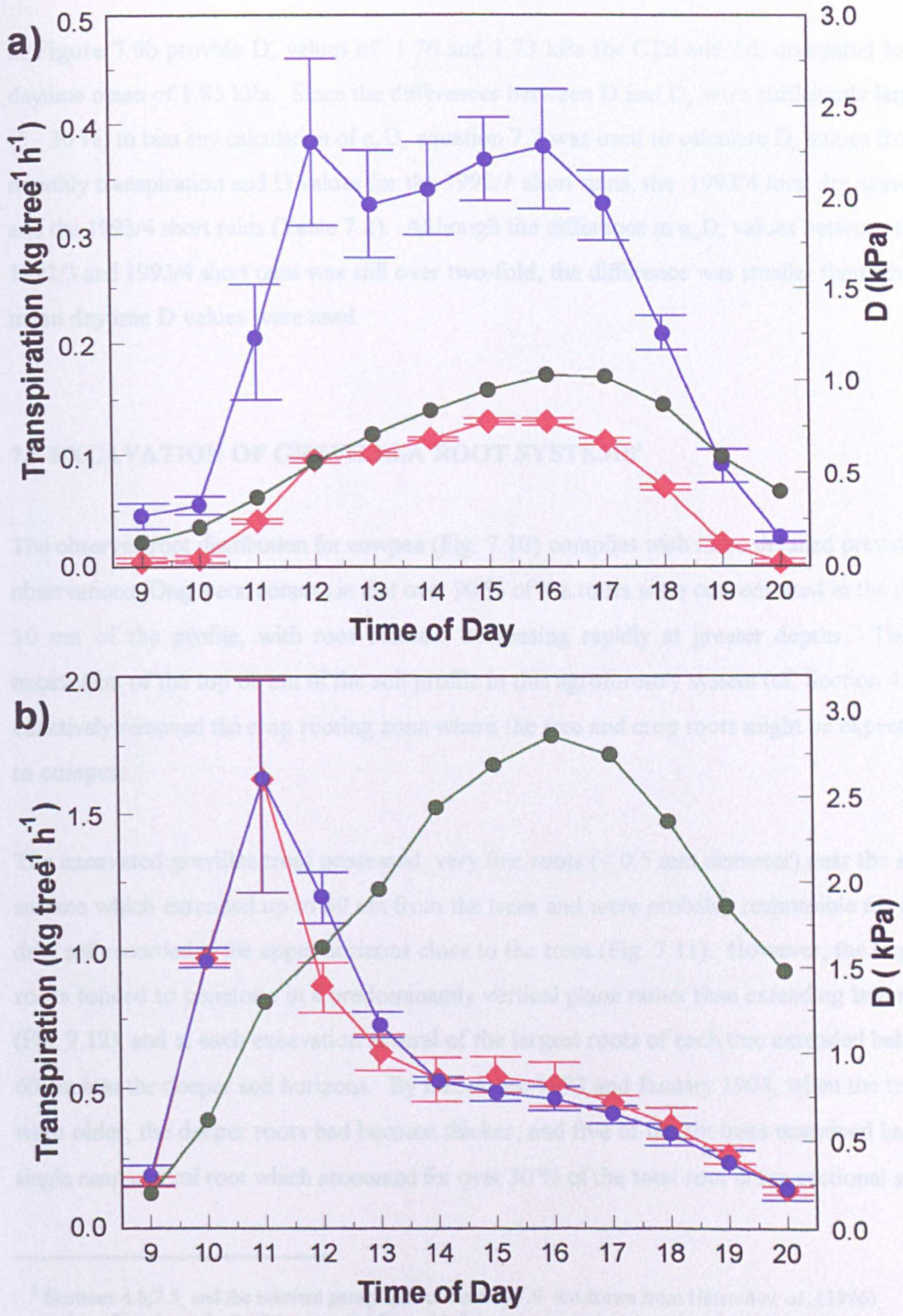


Figure 7.9 Diurnal timecourses of transpiration in grevillea and saturation vapour pressure deficit (D, ●) for treatments Td (●) and CTd (◆); (a) early in the 1992/3 (29/11/92) short rains when mean daytime D was low on the day following substantial rainfall on well-charged soil (0.64 kPa, 22 mm) and; (b) near the end of the 1993/4 (29/01/94) short rains when mean daytime D was high (1.85 kPa), 34 days after the last rainfall event. Vertical bars represent double standard errors of the means.

in Figure 7.9b provide D_e values of 1.76 and 1.73 kPa for CTd and Td, compared to a daytime mean of 1.85 kPa. Since the differences between D and D_e were sufficiently large (5 - 30 %) to bias any calculation of e_wD, equation 7.2 was used to calculate D_e values from monthly transpiration and D values for the 1992/3 short rains, the 1993/4 long dry season and the 1993/4 short rains (Table 7.2). Although the difference in e_wD_e values between the 1992/3 and 1993/4 short rains was still over two-fold, the difference was smaller than when mean daytime D values were used.

7.3 EXCAVATION OF GREVILLEA ROOT SYSTEMS[1]

The observed root distribution for cowpea (Fig. 7.10) complies with more detailed previous observations (Ong, pers. comm.) in that over 90 % of the roots were concentrated in the top 30 cm of the profile, with root biomass decreasing rapidly at greater depths. Thus, excavation of the top 60 cm of the soil profile in this agroforestry system (cf. Section 4.8) effectively removed the crop rooting zone where the tree and crop roots might be expected to compete.

The excavated grevillea trees possessed very fine roots (< 0.5 mm diameter) near the soil surface which extended up to 50 cm from the trees and were probably responsible for the drier soil recorded in the upper horizons close to the trees (Fig. 7.11). However, the larger roots tended to penetrate in a predominantly vertical plane rather than extending laterally (Fig. 7.12), and at each excavation several of the largest roots of each tree extended below 60 cm into the deeper soil horizons. By December 1993 and January 1994, when the trees were older, the deeper roots had become thicker, and five of the six trees examined had a single near-vertical root which accounted for over 30 % of the total root cross-sectional area

[1] Sections 4.8,7.3 and the relevant paragraphs of Section 7.9 are drawn from Howard *et. al.*, (1996) and are largely unchanged; however additional information on materials and methods is provided in Section 4.8.

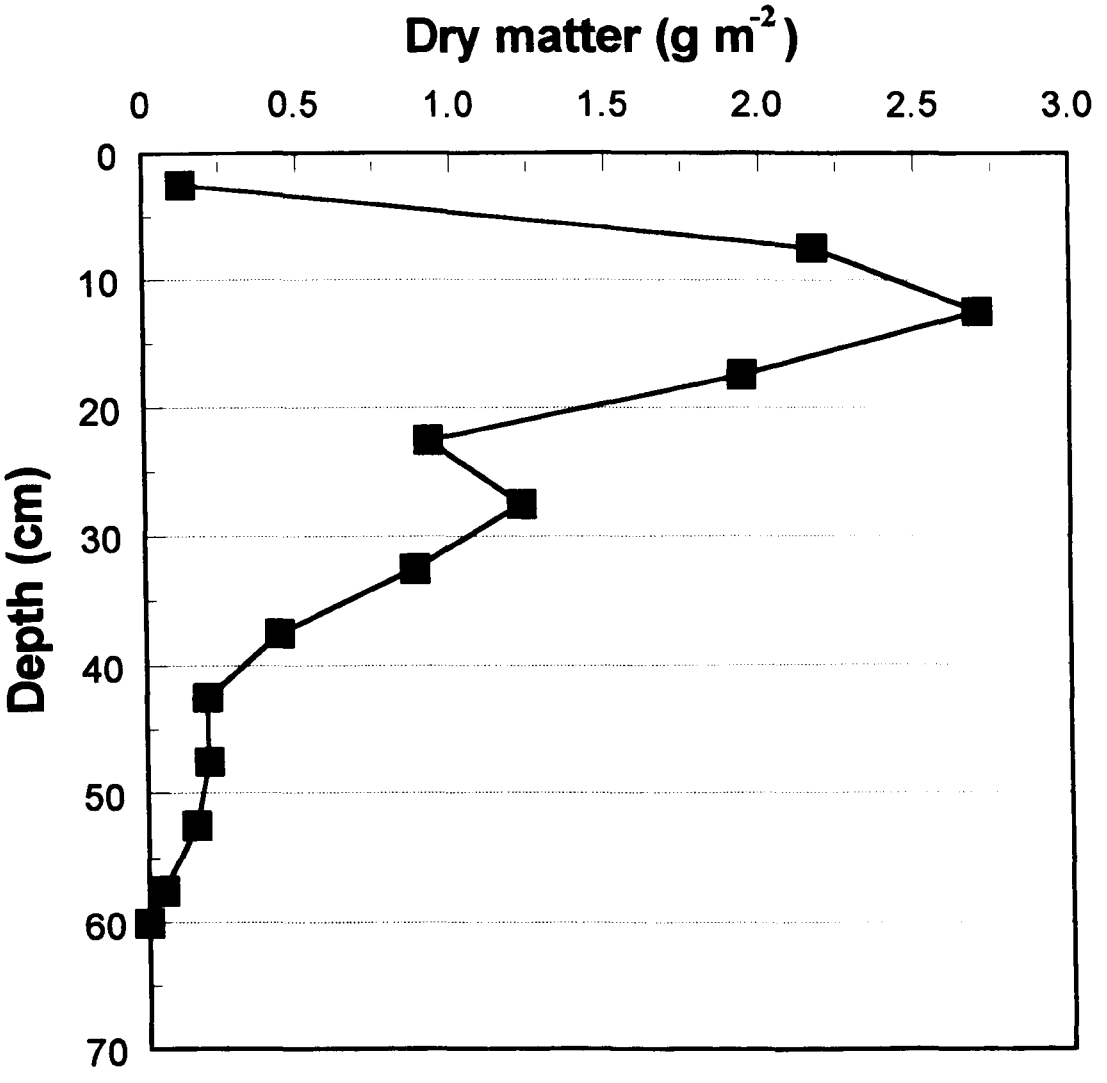


Figure 7.10 Distribution of root dry matter with depth for sole cowpea (*Vigna unguiculata*) at 60 DAS during the short rains, 1993/4.

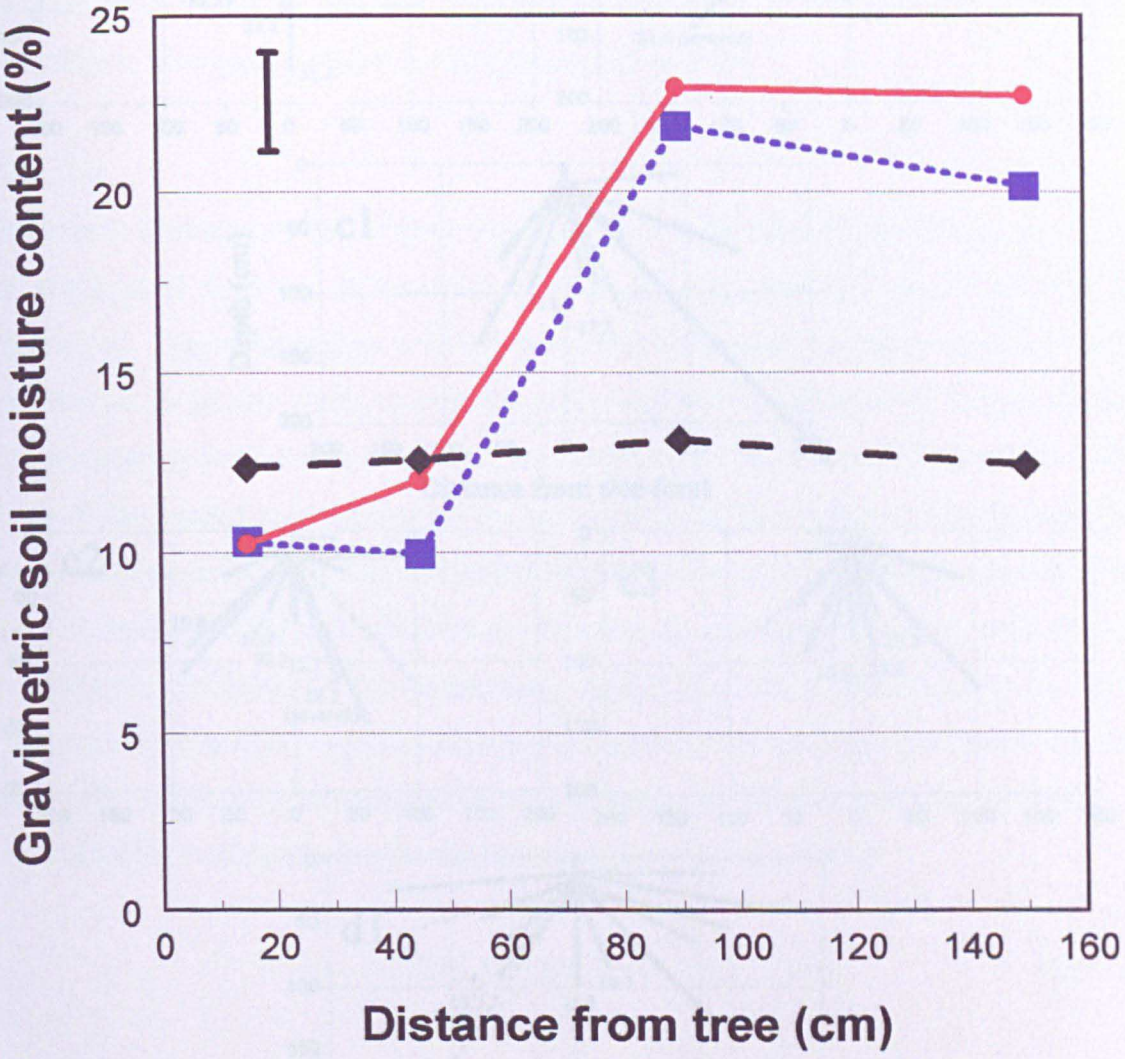


Figure 7.11 Gravimetric soil moisture content at various distances from 16 month old *Grevillea robusta* trees and at depths of 0-20 (■), 20-40 (●) and 40-60 cm (◆) in December 1993. The vertical bar represents the standard error of the difference (SED).

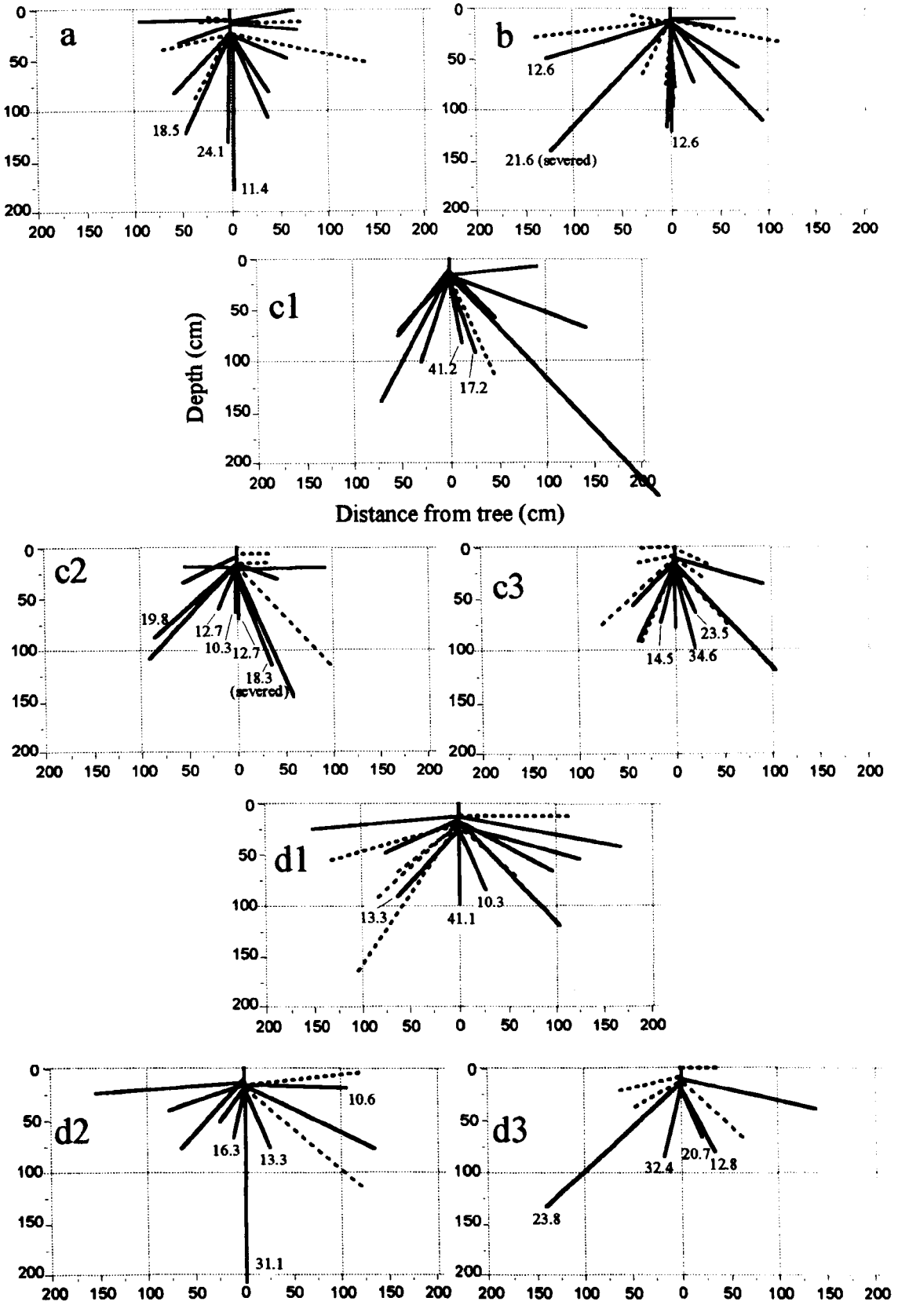


Figure 7.12 Root projections of *Grevillea robusta* trees excavated to a depth of 60 cm at 10 (a and b), 16 (c1, c2 and c3) and 18 months (d1, d2 and d3) after planting. Lengths for broken roots and roots extending below the excavated depth were estimated (see text for details). Roots with cross-sectional areas contributing less than 1 % of the total are represented by the dashed lines, those contributing over 1 % are represented by solid lines and those contributing more than 10 % are marked by their percentages.

(Figs. 7.12 c1-c3 and d1-d3). If this trend continued, mature trees would possess a dominant deep taproot, two or three large subsidiary sinker roots and relatively few superficial lateral roots; this was confirmed by excavation of the roots of a 12 year old grevillea at Machakos research station (data not presented).

Sap flux

In order to estimate the effect of excavation on sap flux, the relationship between sap fluxes in the control trees and those which were to be excavated was established prior to excavation. These relationships were not necessarily consistent throughout the day because differences in canopy structure and orientation influenced the extent of mutual shading experienced by individual trees at different times of day. Where such differences existed, time of day needed to be accounted for in modelling sap flux relative to the unexcavated trees. Multiple linear regression was performed using Genstat and the models providing the best fit were selected. The variables employed in the modelling procedure were the half hourly mean sap fluxes for the control trees, time of day, and their respective quadratics. These models were used to predict the expected sap fluxes for the excavated trees if they had been left undisturbed; these values were then compared with the measured sap fluxes. A typical model is shown below for the first excavation (21 May 1993):

$$S_f = 0.393C_1 + 1.05C_2 - 0.2692t^2 + 22.1 \qquad \textbf{(Eq. 7.3)}$$

where S_f is modelled sap flux (g h^{-1}), C_1 and C_2 represent the sap fluxes for control trees (g h^{-1}) and t is the time of day. Standard errors for C_1, C_2, t^2 and the constant were 0.158, 0.179, 0.0727 and 13.9 respectively (with a variance ratio of 872.9 and 44 degrees of freedom; the percentage of the variance accounted and the estimated standard error of observations were 98.2 and 19.3 respectively).

Figure 7.13 shows the measured and modelled sap fluxes before and after the first excavation and demonstrates that the sap flux of the excavated trees can be modelled with a high degree

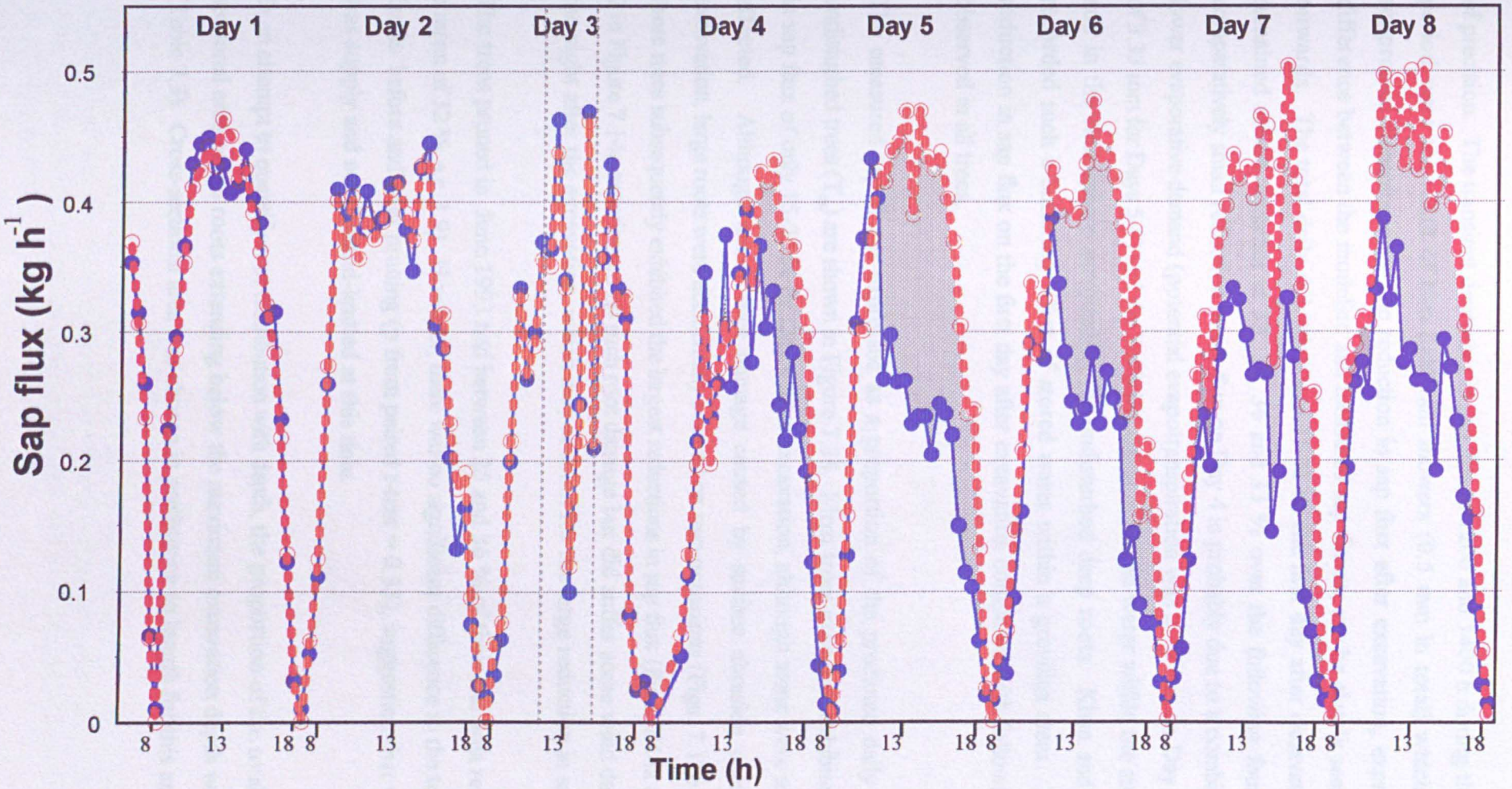


Figure 7.13 Modelled (○) and measured (●) sap fluxes for a 10 month old *Grevillea robusta* tree for the three day period preceding and the five day period following removal of the crop rooting zone: the excavation period is denoted by the vertical dotted lines. The shaded area represents the estimated reduction in sap flux resulting from excavation. NB. only the period from 800 to 1800 hours is shown for each day.

of precision. The transient decreases in sap flux at 1200 and 1400 h during the excavation period were the result of two light rain showers (0.5 mm in total) which temporarily suppressed transpiration. The reduction in sap flux after excavation, expressed as the difference between the modelled and measured sap fluxes, can be clearly seen from day 4 onwards. The total daily reduction was 15 % on the first day after excavation and then remained almost constant at 33, 34, 36 and 33 % over the following four days. The comparatively small reduction in sap flux on Day 4 is probably due to a combination of the lower evaporative demand (potential evapotranspiration was 2.70 mm on Day 4 vs. a mean of 3.33 mm for Days 5-8) and the buffering effect of stored water within the stem and roots and in the rhizosphere surrounding the undisturbed deep roots. Khan and Ong (1995) recorded such a buffering effect of stored water within a grevillea stem. The smaller reduction in sap flux on the first day after excavation compared with following days was observed in all trees.

The measured sap fluxes expressed as a proportion of the predicted daily sap flux for undisturbed trees (T_{cc}) are shown in Figure 7.14. Most trees examined exhibited reductions in sap flux of only 15-20 % by Day 4 after excavation, although some were more severely affected. Although minor root damage caused by surface abrasion occurred during excavation, large roots were accidentally severed on two occasions (Figs. 7.12b and c2), and these trees subsequently exhibited the largest reductions in sap flux (Figs. 7.14a and b). Tree 2 in Figure 7.14c experienced no such root damage but did suffer some wind damage during the night after the excavation, which may account for the large reduction in sap flux.

The trees pruned in June 1993 had between 25 and 36 % of their leaf area removed (with a mean of 32 %, s.e. 1.9). However, there was no significant difference in the total daily sap fluxes before and after pruning (p from paired t-test = 0.33), suggesting that water uptake was supply and not demand-limited at this time.

In an attempt to quantify root distribution with depth, the proportion of the total basal cross-sectional area of the roots extending below the maximum excavation depth was calculated (Table 7.3). Cross-sectional area was chosen in preference to length for this analysis on the

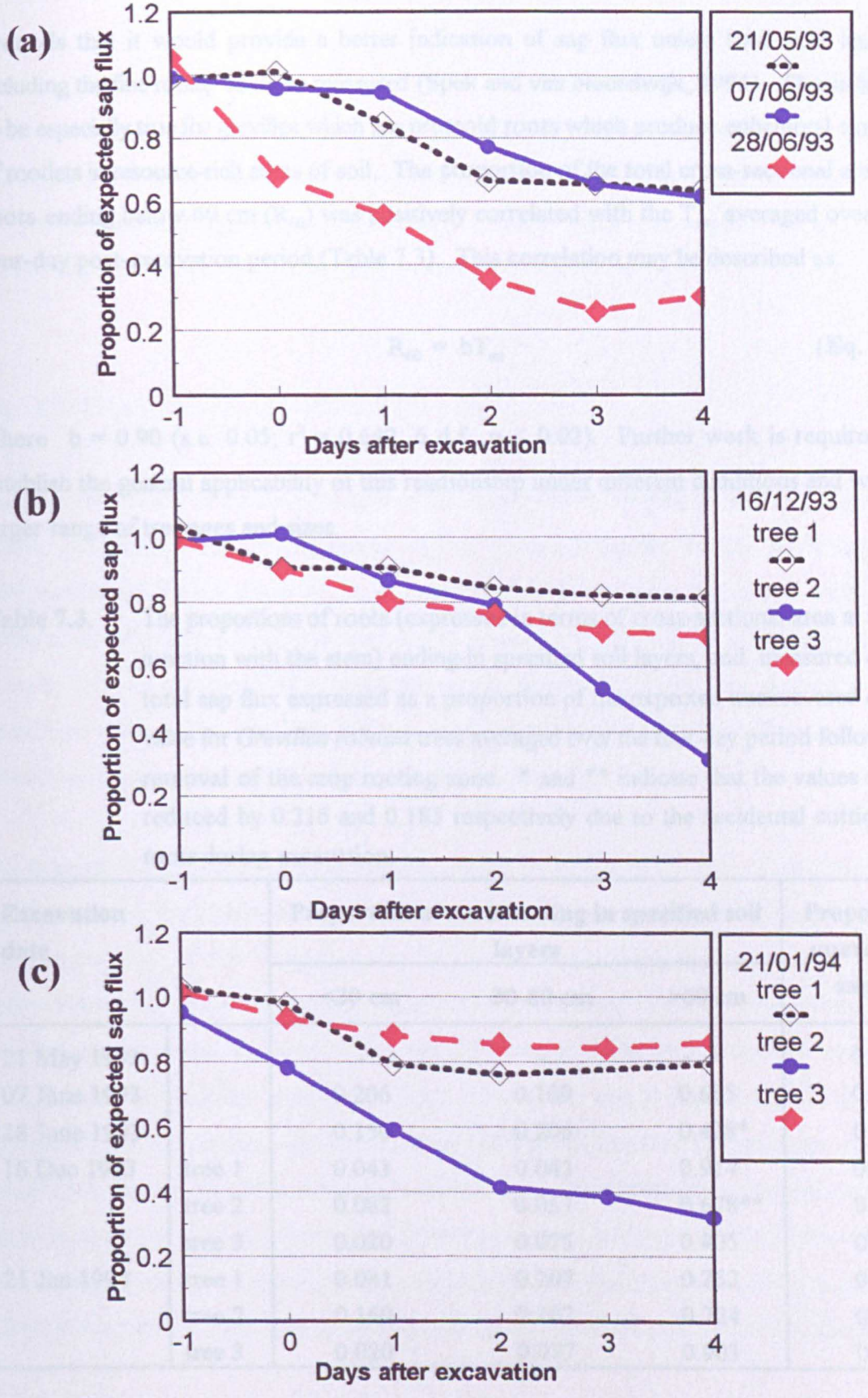


Figure 7.14 Daily total sap flux of a) 10 month, b) 16 month and c) 18 month old *Grevillea robusta* trees expressed as a fraction of the values for unexcavated control trees for the period extending from one day before to four days after removal of the crop rooting zone.

grounds that it would provide a better indication of sap flux unless total root length, including the fine roots, could be measured (Spek and van Noordwijk, 1994). This is likely to be especially true for grevillea which has proteoid roots which produce ephemeral clumps of rootlets in resource-rich areas of soil. The proportion of the total cross-sectional area of roots ending below 60 cm (R_{60}) was positively correlated with the T_{ex} averaged over the four-day post-excavation period (Table 7.3). This correlation may be described as:

$$R_{60} = bT_{ex} \qquad \textbf{(Eq. 7.4)}$$

where $b = 0.90$ (s.e. 0.05; $r^2 = 0.642$, 6 d.f., $p < 0.02$). Further work is required to establish the general applicability of this relationship under different conditions and with a larger range of tree ages and sizes.

Table 7.3. The proportions of roots (expressed in terms of cross-sectional area at their junction with the stem) ending in specified soil layers, and measured daily total sap flux expressed as a proportion of the expected unexcavated daily value for *Grevillea robusta* trees averaged over the four day period following removal of the crop rooting zone. * and ** indicate that the values were reduced by 0.216 and 0.183 respectively due to the accidental cutting of roots during excavation.

Excavation date		**Proportion of roots ending in specified soil layers**			**Proportion of unexcavated sap flux**
		<30 cm	**30-60 cm**	**>60 cm**	
21 May 1993		-	-	-	0.701
07 June 1993		0.206	0.109	0.685	0.746
28 June 1993		0.150	0.206	0.428*	0.368
16 Dec 1993	tree 1	0.043	0.043	0.914	0.846
	tree 2	0.082	0.057	0.678**	0.625
	tree 3	0.020	0.075	0.905	0.742
21 Jan 1994	tree 1	0.041	0.207	0.752	0.781
	tree 2	0.169	0.107	0.724	0.427
	tree 3	0.020	0.077	0.903	0.857

The mean reduction in sap flux following excavation of the grevillea roots to 60 cm was 27 % during the 1993/4 short rains. Given that the seasonal water use by the CTd trees was 46 mm, these results suggest that approximately 12 mm of water was removed directly from the rooting zone of the cowpea by the grevillea.

7.4 ESTIMATION OF CROP WATER USE

In the absence of any direct measurement of transpiration for cowpea, its above-ground dry matter production and the saturation vapour pressure deficit records were used in combination with the dry matter:water use ratio to estimate seasonal transpiration. Although Adiku *et al.* (1995) have previously used an e_wD value of 5 g kg^{-1} kPa for modelling cowpea growth, this was obtained under non-limiting conditions of water and nutrients. An alternative value of 3.7 g kg^{-1} kPa for groundnut grown under dryland conditions (Squire, 1990) was therefore also used in Table 7.4 for comparison.

The inherent contradiction of an apparently greater water use at the time of maximum dry weight than at final harvest is an artefact of the calculation; since senescence and the consequent loss of dry weight during the latter part of the season resulted in an underestimation of the true water use. If the glucose equivalent yields for cowpea had been used instead of biomass, the disparity between the W and e_t values for the times of maximum weight and final harvest would have been smaller. As stated previously, the glucose equivalent provides an estimate of the quantity of glucose required to synthesize the seed constituents such as oils and proteins as compared to the predominantly structural materials found in vegetative tissues. Morris *et al.* (1990) used a glucose equivalent 1.35 for cowpea seed. The e_t values for the period up to maximum crop dry weight are more likely to provide a better estimate of water use by cowpea than those obtained at final harvest due to the

errors associated with the senescence and loss of above-ground material during the latter stages of the season. However, as some water would inevitably have been used between the time of maximum dry weight and final harvest, even the higher values for water use are likely to be an underestimate of the true values.

Table 7.4 Above-ground dry matter production at the time of maximum weight and at final harvest (W), mean daytime (0800 - 1800 h) saturation vapour pressure deficit for the appropriate period (D), and estimated water use (e_t) for cowpea in treatments Cg and CTd during the 1992/3 and 1993/4 short rains.

Treatment		W	D	e_{t1}	e_{t2}
		g m^{-2}	kPa	kg m^{-2}	kg m^{-2}
Short rains 1992/3					
Cg	Max. wt.	171	0.77	26.4	35.7
CTd		169	0.77	26.1	35.3
Cg	Harvest	143	0.73	21	28.4
CTd		156	0.73	22.9	31
Short rains 1993/4					
Cg	Max. wt.	198	0.88	34.9	47.2
CTd		111	0.88	19.6	26.5
Cg	Harvest	148	1.08	31.9	43.1
CTd		64	1.08	13.8	18.6

NB. e_{t1} and e_{t2} were calculated using W values and e_wD values of 5 g kg^{-1} k Pa as used by Adiku *et al.* (1995) for cowpea and 3.7 g kg^{-1} k Pa the mean value for groundnut (Squire, 1991).

7.5 SOIL EVAPORATION

Microlysimeter measurements

During the 1992/3 short rains (including the week before planting), rainfall occurred on 73 days out of 109. However, although e_s could not be measured reliably on days when heavy

rainfall occurred between microlysimeter weighings, Daamen (1991) reported that microlysimeters remained representative following showers of up to 5 mm; when light showers of <5 mm occurred between weighings, it was therefore assumed that the microlysimeters received an equivalent quantity of rainfall.

Mean daily measured e_s values were not significantly different in Td and Cg treatments when compared over the entire season (2.7 and 2.6 mm d^{-1}; $t = 1.25$, d.f. 95, $p > 0.2$ from paired two-tail t-test). However, the measured e_s values were significantly different ($t = 2.32$, d.f. 32, $p < 0.05$) between 40 - 75 days after sowing (2.7 and 2.4 mm d^{-1}), when the leaf area index of cowpea exceeded 1 in Cg, although evaporation was only 6 % greater in Td. There was no significant difference between Td and Cg during the four weeks after the crop harvest ($t = 0.36$, d.f. 26, $p > 0.7$), suggesting that the grevillea had no measurable effect on soil evaporation at this time, when the leaf area index for Td grevillea was only about 0.2.

Estimation of e_s and the Ritchie model

Throughout the period of relatively high LAI in cowpea (40 - 70 DAS), there was only one interval when rainfall did not occur on consecutive days and therefore only one drying cycle during this period. Since the measured e_s values for the Td treatment were only 6 % greater than in the sole cowpea over a relatively short period (40 - 75 DAS), the seasonal mean e_s values were used in ensuing calculations. In order to establish the parameters for the Ritchie model (Section 1.5 and Eq. 7.5), e_s values for periods when there were no showers between measurements were used, giving a total of six drying cycles throughout the season, varying in length from 2 - 9 days. The mean measured e_s value for the first day after rainfall was used to define U, or the quantity of water lost during first stage evaporation, and t_1 was assumed to be 1 day. The slope of the line of best fit obtained from linear regression analysis of cumulative e_s (after first stage evaporation) against the square root of $t - t_1$ ($r^2 = 0.92$, n = 32) was used to derive α, as described by the following equation:

$$\sum e_s = U + \alpha \sqrt{(t - t_1)} \qquad \textbf{(Eq.7.5)}$$

where U = 4.85 and α = 3.83 (s.e. 0.13 and 0.10 respectively).

Daamen (1991) stated that, although the Ritchie model provided reasonable estimates of e_s over periods of several days or weeks, the values obtained did not appear to be clearly divisible into first and second stage evaporation phases. This also appeared to be the case for the Machakos field data and, as an alternative to the Ritchie model, a linear regression analysis of the cumulative e_s values against the square root of t was performed, resulting in the following equation:

$$\sum e_s = a + b\sqrt{t} \qquad \textbf{(Eq. 7.6)}$$

(a = -0.92 and b = 6.09 with standard errors of 0.46 and 0.23 respectively, $r^2 = 0.95$, d.f. 32). Figure 7.15 shows the measured and estimated cumulative values of e_s obtained using equations 7.5 and 7.6; although both provided accurate estimates of cumulative evaporation, the simple linear regression described by equation 7.6 was more accurate at higher cumulative e_s values. Both equations produced similar results but, whereas equation 7.5 assumes a two-stage evaporation pattern in its derivation, equation 7.6 merely assumes that e_s decreases proportionately to the square root of the time since the last re-wetting of the soil surface. Despite the apparently slightly greater accuracy of equation 7.6, the Ritchie model (Eq. 7.5) was used to estimate soil evaporation, in accordance with accepted practice, between the start of the 1992/3 short rains and the end of the 1993/4 short rains.

1992/3 short rains

Figure 7.16 shows cumulative soil evaporation calculated using equation 7.5 and rainfall distribution during the 1992/3 short rains. The high frequency of moderate rainfall events is illustrated by Figure 7.17; the median and mean daily total rainfall values for the 73 days when rain occurred were respectively 4.5 and 10.4 mm. The high frequency of rainfall led to almost continual re-wetting of the soil and e_s was maintained at a correspondingly high rate (i.e. first stage evaporation) for most of the season. Cumulative e_s accounted for up to

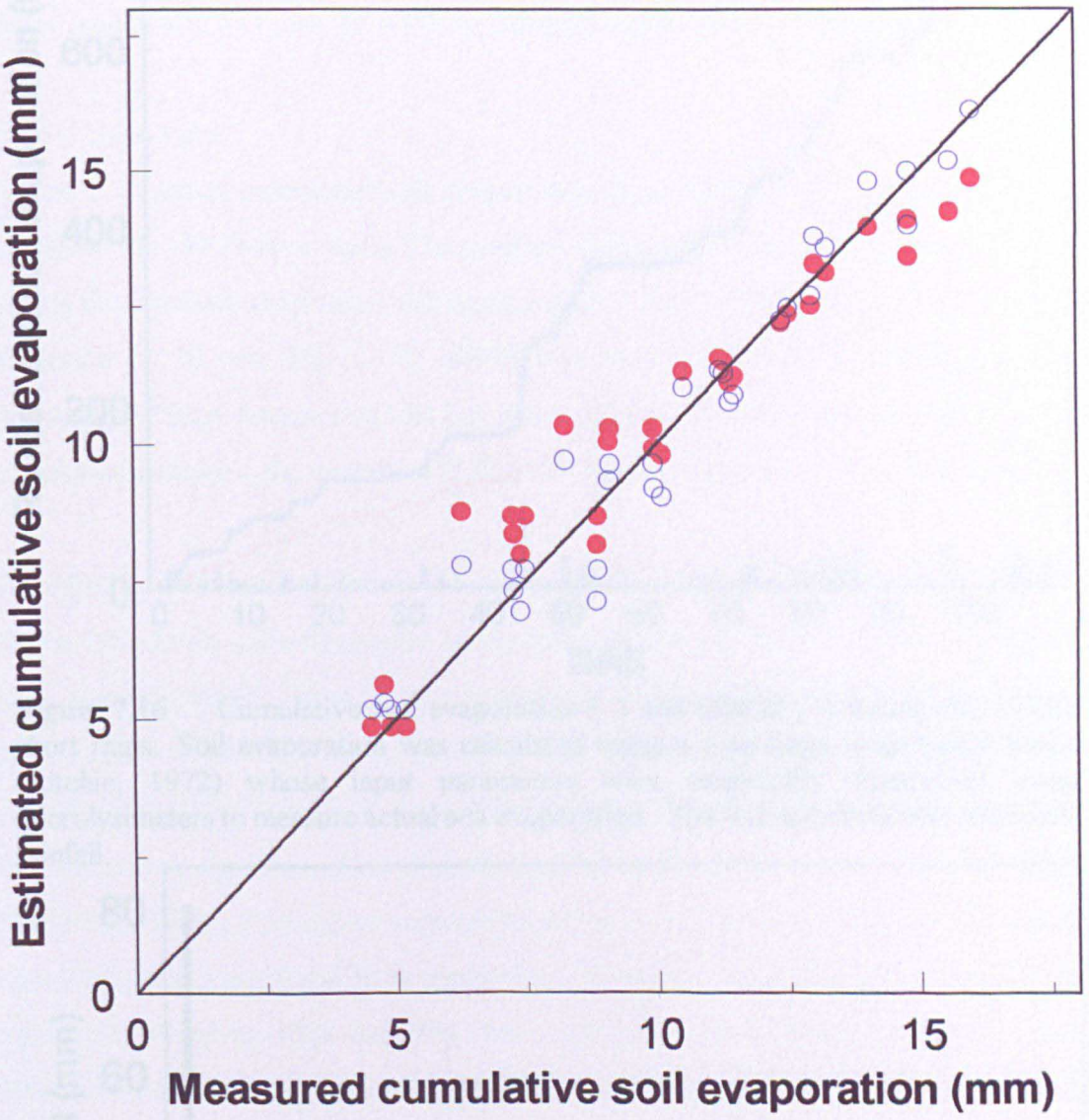


Figure 7.15 Relation between cumulative soil evaporation (e_s) from lysimeter measurements and e_s obtained by linear regression analysis of cumulative e_s against the square root of time since last rewetting of the soil (○) and a Ritchie model (●); see text for equations . The 1:1 line is shown.

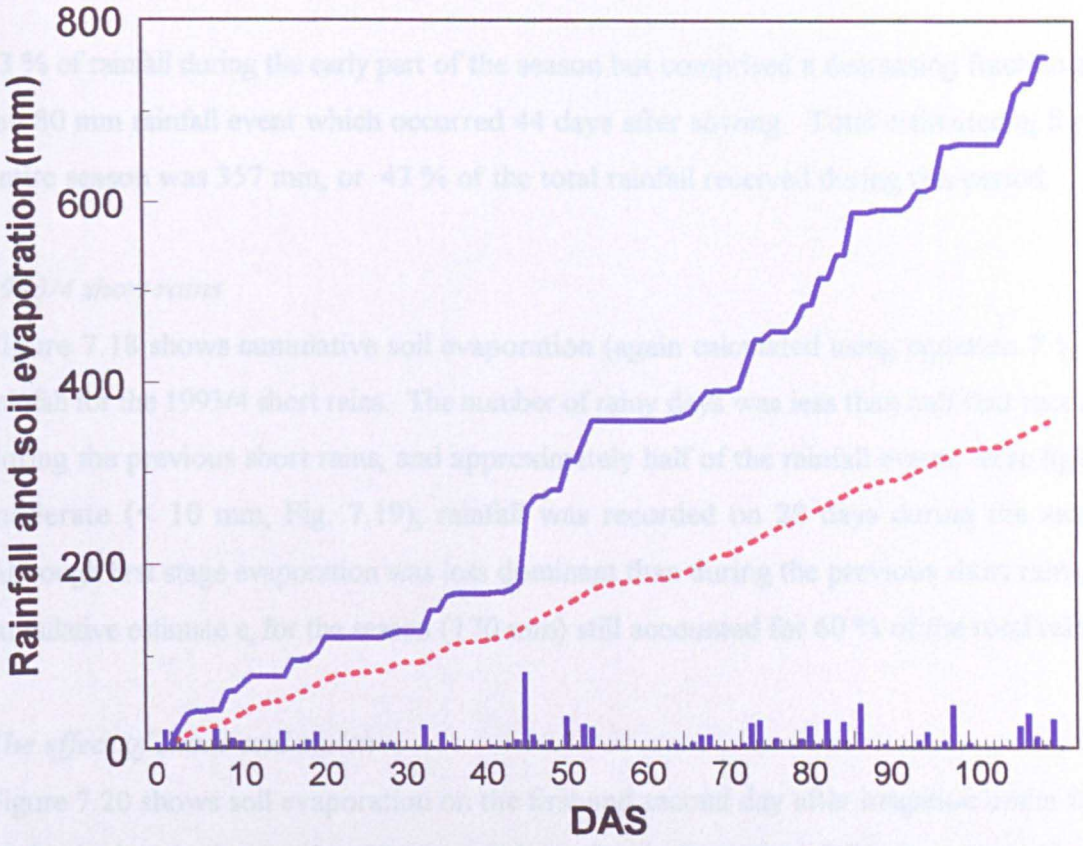


Figure 7.16 Cumulative soil evaporation (-) and rainfall (—) during the 1992/3 short rains. Soil evaporation was calculated using a two-stage evaporation model (Ritchie, 1972) whose input parameters were empirically determined using microlysimeters to measure actual soil evaporation. The histograms denote total daily rainfall.

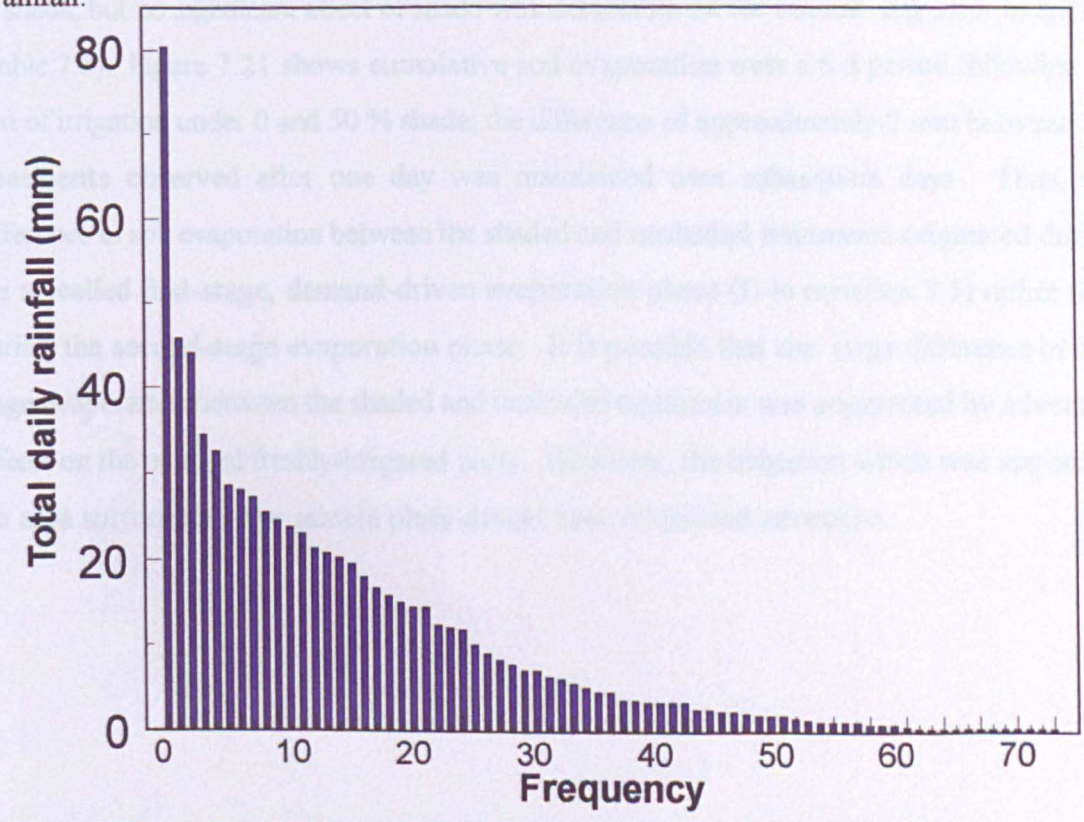


Figure 7.17 Total daily rainfall and frequency during the 1992/3 short rains.

73 % of rainfall during the early part of the season but comprised a decreasing fraction after the 80 mm rainfall event which occurred 44 days after sowing. Total estimated e_s for the entire season was 357 mm, or 47 % of the total rainfall received during this period.

1993/4 short rains

Figure 7.18 shows cumulative soil evaporation (again calculated using equation 7.5) and rainfall for the 1993/4 short rains. The number of rainy days was less than half that recorded during the previous short rains, and approximately half of the rainfall events were light or moderate (< 10 mm, Fig. 7.19); rainfall was recorded on 29 days during the season. Although first stage evaporation was less dominant than during the previous short rains, the cumulative estimate e_s for the season (170 mm) still accounted for 60 % of the total rainfall.

The effect of shade and mulch

Figure 7.20 shows soil evaporation on the first and second day after irrigation under 0 and 50 % shade (obtained using 50 % neutral density shade netting) following applications of 0, 2.25 and 4.5 t ha^{-1} of grevillea mulch. e_s was significantly reduced by shade on the first day after irrigation (Table 7.5), from 6.3 mm d^{-1} under zero shade to 4.0 mm d^{-1} under 50 % shade, but no significant effect of shade was detectable on the second day after irrigation (Table 7.6). Figure 7.21 shows cumulative soil evaporation over a 6 d period following 20 mm of irrigation under 0 and 50 % shade; the difference of approximately 2 mm between the treatments observed after one day was maintained over subsequent days. Thus, the difference in soil evaporation between the shaded and unshaded treatments originated during the so called first-stage, demand-driven evaporation phase (U in equation 7.5) rather than during the second-stage evaporation phase. It is possible that the large difference in first stage evaporation between the shaded and unshaded treatments was augmented by advective effects on the exposed freshly-irrigated plots. However, the irrigation which was applied to the area surrounding the sample plots should have minimised advection.

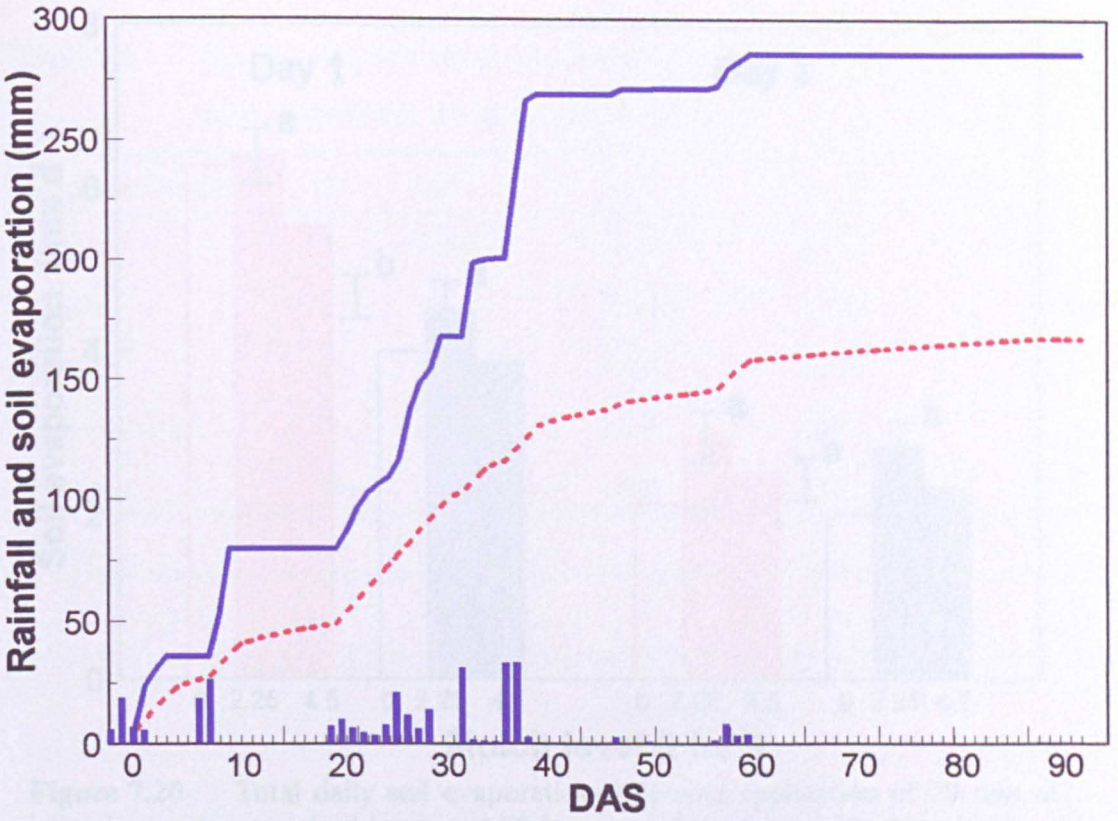


Figure 7.18 Cumulative soil evaporation (---) and rainfall (—) during the 1993/4 short rains. Soil evaporation was calculated using a two-stage evaporation model (Ritchie, 1972) whose input parameters were empirically determined using microlysimeters to measure actual soil evaporation. The histograms denote total daily rainfall.

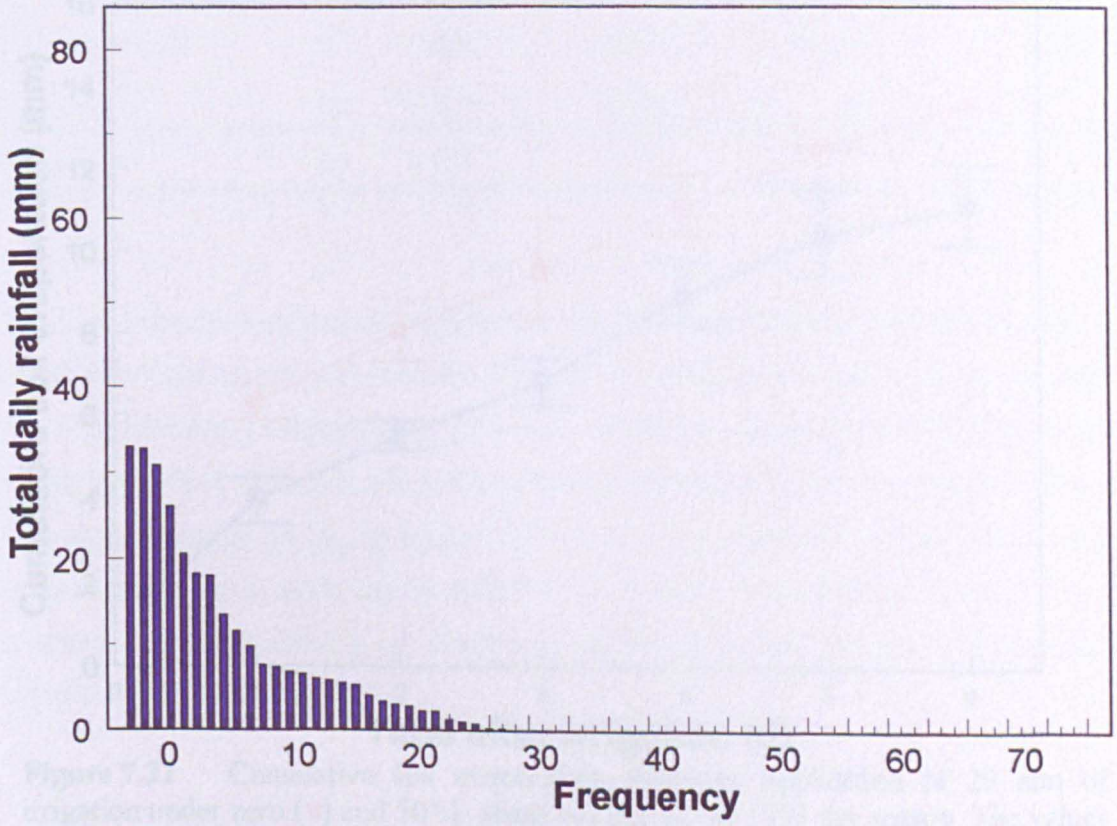


Figure 7.19 Total daily rainfall and frequency during the1993/4 short rains. The axes are the same as for Fig. 7.17 for comparison.

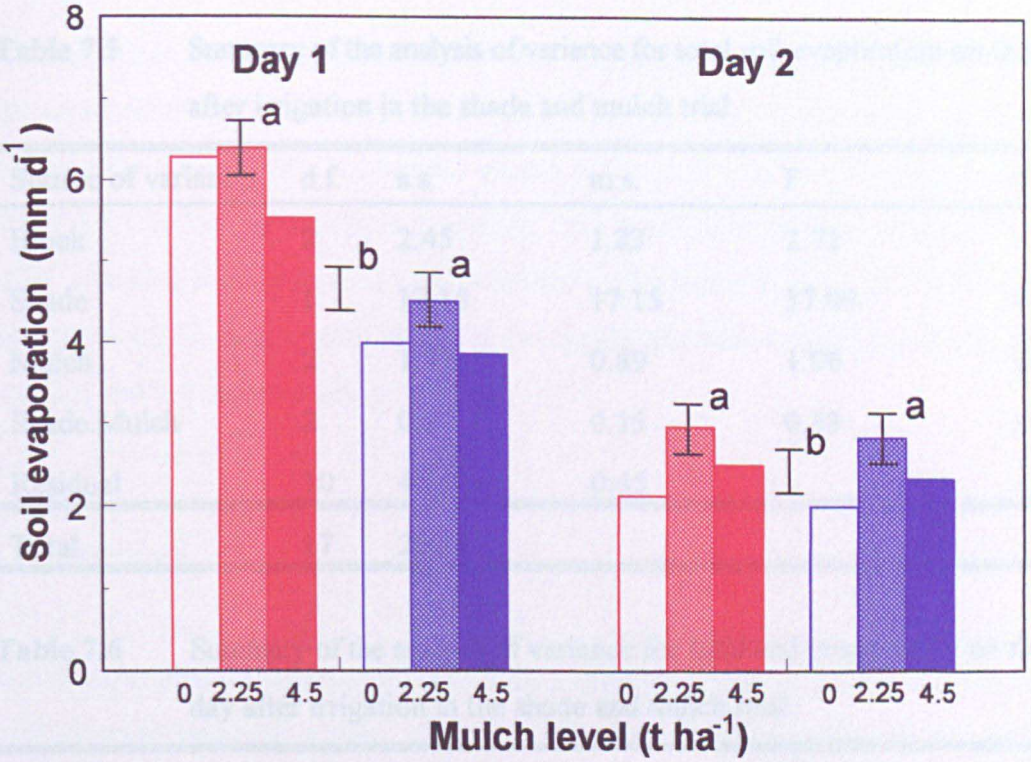


Figure 7.20 Total daily soil evaporation following application of 20 mm of irrigation under zero (red bars) and 50 % shade (blue bars) with three levels of grevillea mulch during the 1993 dry season. The vertical bars represent double standard errors of the difference between the means for different levels of mulch (a) or shade (b).

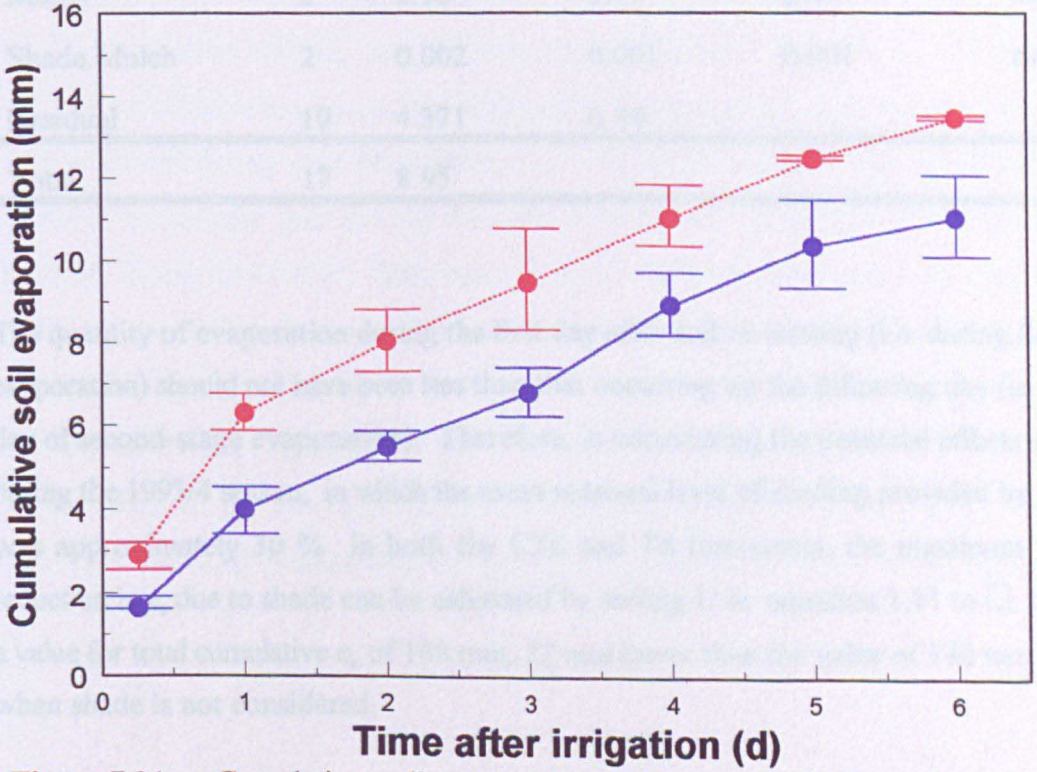


Figure 7.21 Cumulative soil evaporation following application of 20 mm of irrigation under zero (●) and 50 % shade (●) during the 1993 dry season. The values are the means for three drying cycles and the vertical bars represent double standard errors of the mean.

Table 7.5 Summary of the analysis of variance for total soil evaporation on the first day after irrigation in the shade and mulch trial.

Source of variation	d.f.	s.s.	m.s.	F	Sig.
Block	2	2.45	1.23	2.72	
Shade	1	17.15	17.15	37.99	0.001
Mulch	2	1.77	0.89	1.96	ns (0.19)
Shade.Mulch	2	0.3	0.15	0.33	ns (0.73)
Residual	10	4.51	0.45		
Total	17	26.18			

Table 7.6 Summary of the analysis of variance for total soil evaporation on the second day after irrigation in the shade and mulch trial.

Source of variation	d.f.	s.s.	m.s.	F	Sig.
Block	2	2.31	1.15	2.64	
Shade	1	0.09	0.09	0.21	ns (0.66)
Mulch	2	2.18	1.09	2.49	ns (0.13)
Shade.Mulch	2	0.002	0.001	0.001	ns (0.99)
Residual	10	4.371	0.44		
Total	17	8.95			

The quantity of evaporation during the first day after soil re-wetting (i.e. during first-stage evaporation) should not have been less than that occurring on the following day (ie. the first day of second-stage evaporation). Therefore, in considering the potential effects of shade during the 1993/4 season, in which the mean seasonal level of shading provided by the trees was approximately 30 % in both the CTd and Td treatments, the maximum potential reduction in e_s due to shade can be estimated by setting U in equation 1.11 to □: this gives a value for total cumulative e_s of 148 mm, 22 mm lower than the value of 170 mm obtained when shade is not considered.

Although there was no significant effect of mulch on soil evaporation (Tables 7.5 and 7.6), this was possibly a consequence of variability and the limited replication available; e_s was consistently greater (with or without shade) in the 2.25 t ha^{-1} mulch treatment than with either 4.5 t ha^{-1} or no mulch on both days 1and 2 and up to the end of the six day drying cycle. Mean percentage ground cover provided by the mulch in the 2.25 and 4.5 t ha^{-1} plots was 70 and 89 %, values which proved to be significantly different using analysis of variance (s.e. 1.6 and 0.5 respectively, $p < 0.001$).

7.6 RUNOFF

Runoff measurements commenced during the 1993/4 short rains. The low frequency of large rainfall events during this season, in which daily total rainfall exceeding 30 mm occurred on only three occasions (Fig. 7.19), resulted in only eight recorded runoff events ranging from < 0.1 to 5 mm. There were no significant differences between treatments in the total runoff (Table 7.7) and the mean total runoff accounted for less than 4 % of the seasonal rainfall. During the previous short rains, with its much higher frequency of storm events and almost three times greater rainfall, runoff would inevitably have been larger. Kiepe (1995) measured runoff from an adjacent trial with similar aspect and soil type, and recorded a total runoff of 64 mm during the 1992/3 short rains. The total rainfall for the 1991/2 short rains was only 20 % greater than that for the 1993/4 short rains; Kiepe (1995) recorded 13 mm of runoff during the 1991/2 short rains, close to the 10.6 mm overall mean recorded in CIRUS for the 1993/4 short rains (Table 7.7), suggesting that runoff from the two trials was similar. Although runoff during the 1992/3 short rains (64 mm) was much greater than in the following short rains (10.6 mm), it still accounted for < 9 % of total seasonal rainfall. Due to the similarities in slope, soil and runoff values, Kiepe's value of 64 mm for the 1992/3 short rains was used as an estimate of runoff from CIRUS during the same period.

Table 7.7 Mean total runoff for sole cowpea (Cg), cowpea with dispersed trees (CTd), cowpea with contour-planted tree rows (CTc) and sole grevillea during the 1993/4 short rains in CIRUS; a summary of the analysis of variance is shown.

Treatment	Total runoff (mm)	s.e.		
Cg	9.1	1.97		
CTd	12.0	2.43		
CTc	9.7	2.45		
Td	12.0	2.47		
Source of variation	**d.f.**	**s.s.**	**m.s.**	**F**	**Sig.**
Treatment	3	19.88	6.63	0.4	ns (0.75)
Residual	8	131.19	16.39		
Total	11	151.07			

7.7 INTERCEPTION

Figure 7.22 shows seed yield for cowpea expressed relative to the mean sole crop yield in the CTa treatment (grevillea trees planted across the contours). The strip (the CTa plots were harvested in 1 m wide strips running across the plots parallel to the tree rows) yields at the same distance from the eastern and western tree rows were significantly different from each other up to 3.5 m away from the trees (t for 3.5 m strips from paired two-tail t-test = 2.55, 7 d.f, $p < 0.05$). The depression in yield relative to the sole crop was greater for the 0.5 - 3.5 m eastern strips than that for the corresponding western strips (44 % reduction in mean yield relative to the sole crop for the eastern strips as opposed to 27 % for the western strips). Figure 7.23 shows that the mean wind direction at times when rainfall was received during the 1993/4 short rains was almost due East (85^0), suggesting that the greater yield depression in the eastern cowpea rows was probably the result of a rain-shadow effect. Although there may have been some redistribution of rainfall, with more rain being received on the windward side of trees, rainfall interception by the tree canopy is likely to have been

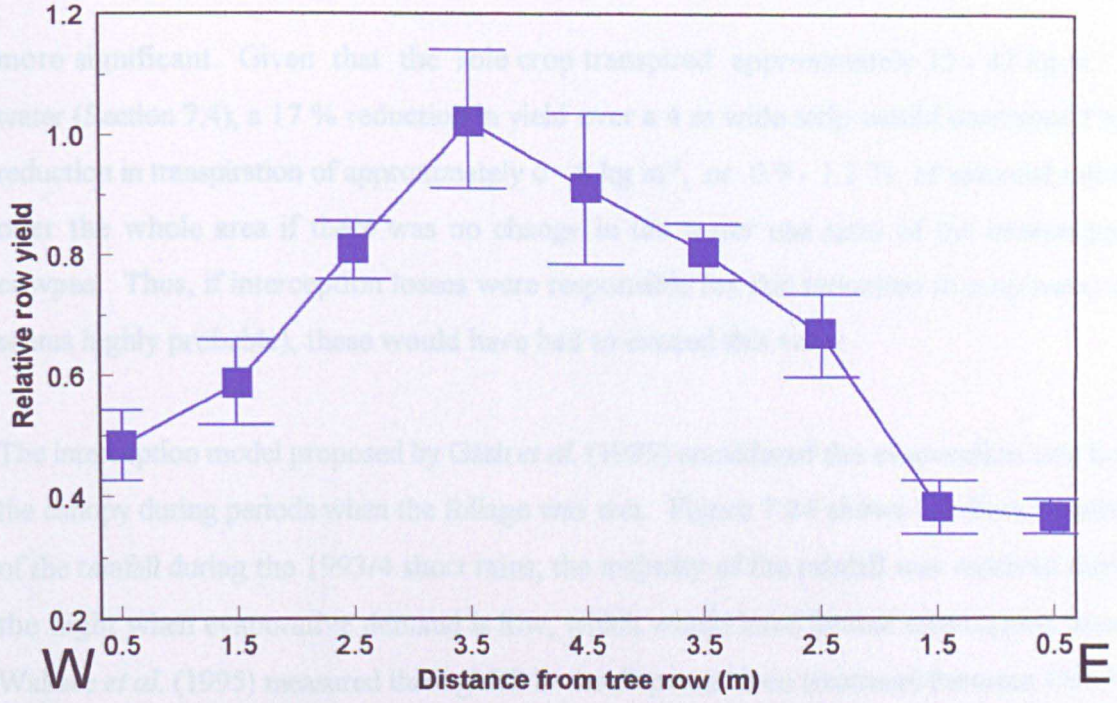


Figure 7.22 Seed yield during the 1993/4 short rains for CTa cowpea. The yield data for individual rows are expressed relative to the mean sole crop yield. The distance from tree row denotes the central position of 1 m wide strips of cowpea running parallel with the tree rows. Vertical bars denote double standard errors of the mean.

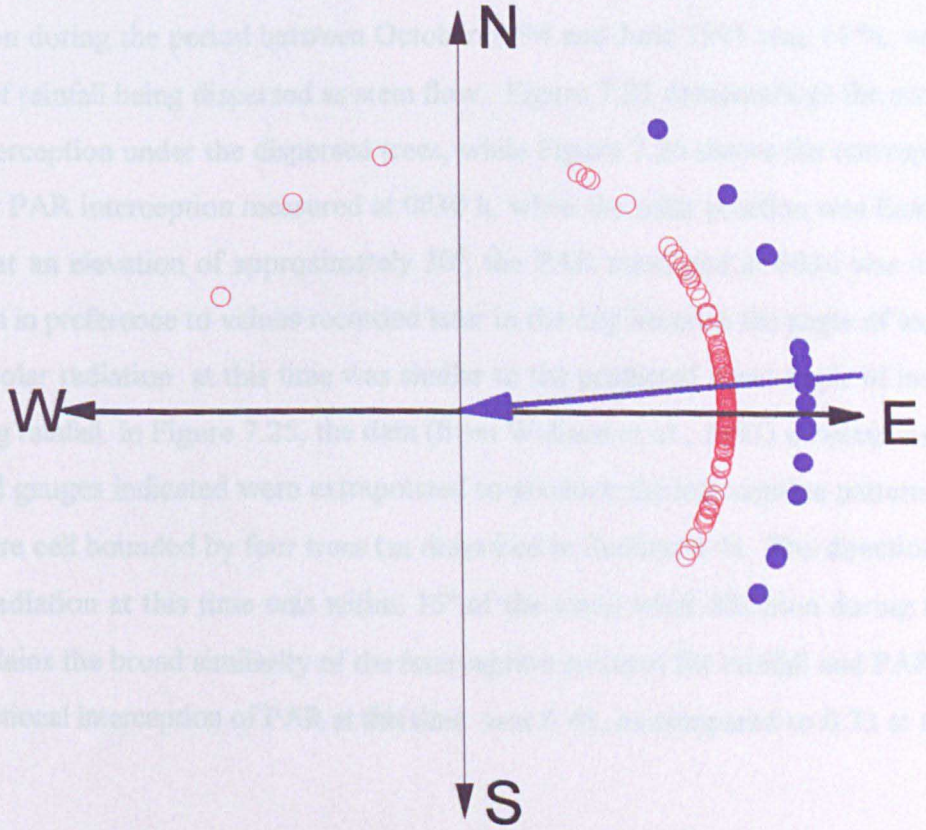


Figure 7.23 Mean wind direction for each hour when less than 5 mm (○) or more than 5 mm (●) rainfall was received during the1993/4 short rains. The blue arrow represents the overall mean wind direction recorded during rainfall events.

more significant. Given that the sole crop transpired approximately 35 - 47 kg m^{-2} of water (Section 7.4), a 17 % reduction in yield over a 4 m wide strip would correspond to a reduction in transpiration of approximately 6 - 8 kg m^{-2}, or 0.9 - 1.3 % of seasonal rainfall over the whole area if there was no change in the water use ratio of the intercropped cowpea. Thus, if interception losses were responsible for this reduction in crop water (as seems highly probable), these would have had to exceed this value.

The interception model proposed by Gash *et al.* (1995) considered the evaporation rate from the canopy during periods when the foliage was wet. Figure 7.24 shows the diurnal pattern of the rainfall during the 1993/4 short rains; the majority of the rainfall was received during the night when evaporative demand is low, which would have limited interception losses. Wallace *et al.* (1995) measured throughfall in the dispersed tree treatment between October 1994 and June 1995. Although this was one year after the 1993/4 short rains, the trees were pruned to maintain a leaf area index of approximately 1, which is of the same order as during the 1993/4 short rains (Ong, pers. comm.); the percentage and pattern of rainfall interception would therefore be expected to have been similar in both seasons. Mean rainfall interception during the period between October 1994 and June 1995 was 14 %, with less than 2 % of rainfall being dispersed as stem flow. Figure 7.25 demonstrates the pattern of rainfall interception under the dispersed trees, while Figure 7.26 shows the corresponding pattern for PAR interception measured at 0830 h, when the solar position was East South East and at an elevation of approximately 30^0; the PAR measured at 0830 was used for comparison in preference to values recorded later in the day because the angle of incidence of direct solar radiation at this time was similar to the predicted mean angle of incidence of incoming rainfall. In Figure 7.25, the data (from Wallace *et al.*, 1995) obtained using the throughfall gauges indicated were extrapolated to produce the interception pattern shown for the entire cell bounded by four trees (as described in Section 4.4). The direction of the incident radiation at this time was within 15° of the mean wind direction during rainfall, which explains the broad similarity of the interception patterns for rainfall and PAR by the trees. Fractional interception of PAR at this time was 0.45, as compared to 0.33 at midday,

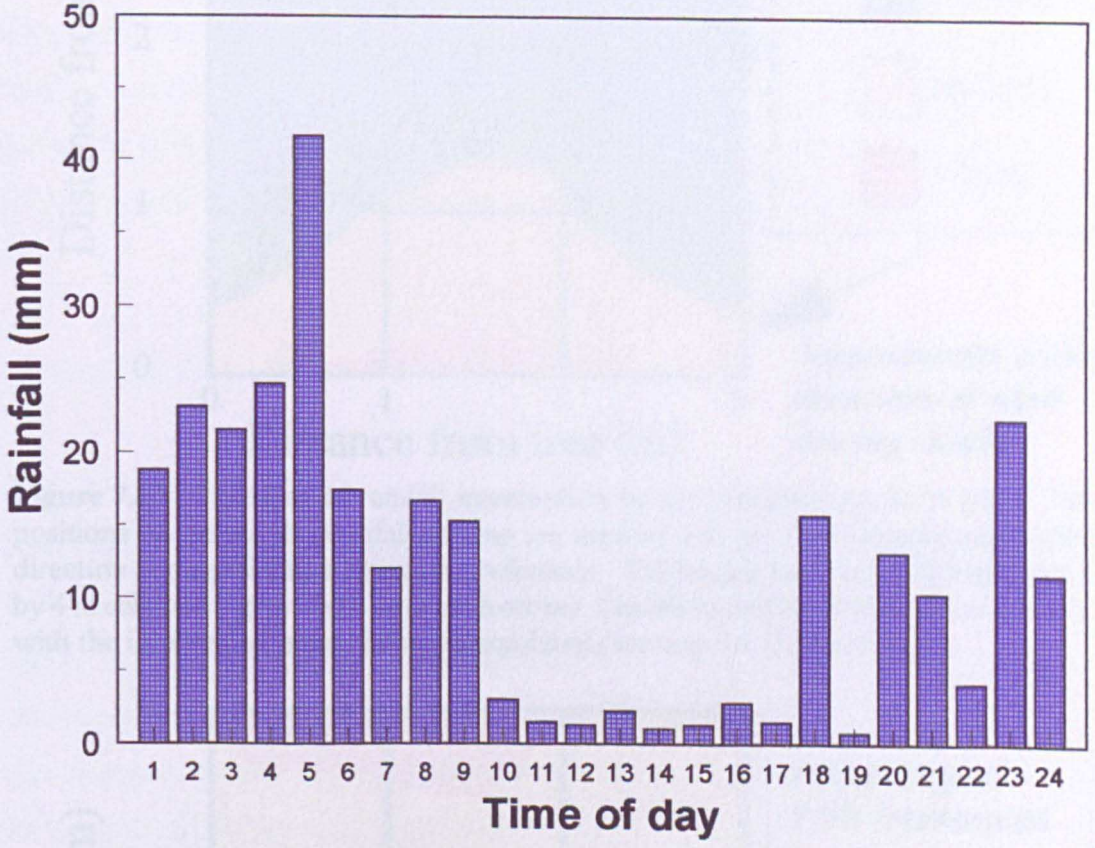


Figure 7.24 Diurnal pattern of the rainfall during the 1993/4 short rains at Machakos. Each bar represents the total rainfall received within specific hours.

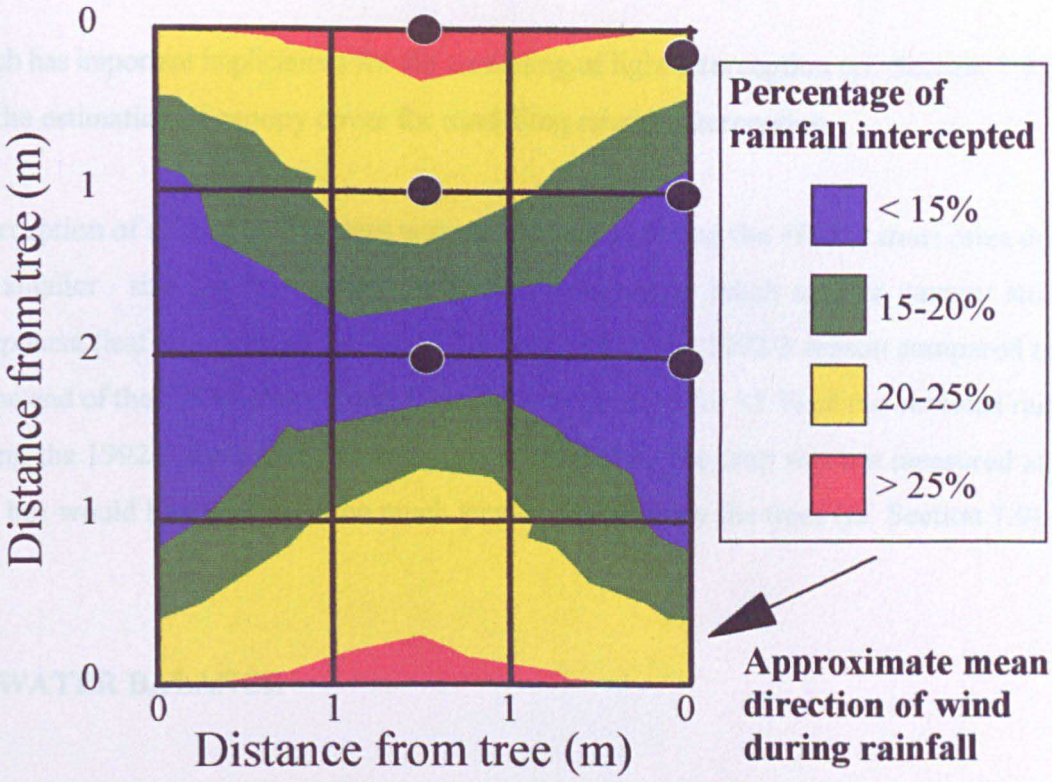


Figure 7.25 Pattern of rainfall interception by the dispersed grevillea trees. The positions of the six throughfall gauges are marked and the approximate mean wind direction during rainfall is shown for reference. The largest rectangle represents the 3 by 4 m cell with a grevillea tree at each corner. The data are from Wallace *et al.* (1995) with the intervening points being interpolated (see text for explanation).

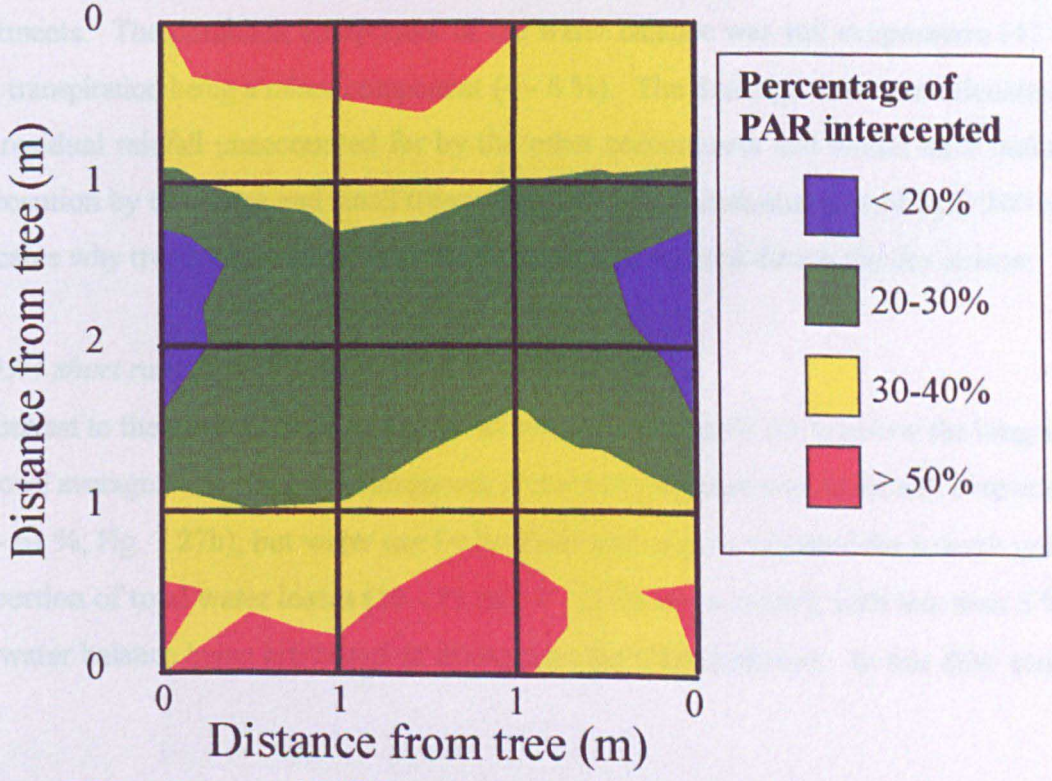


Figure 7.26 Pattern of PAR interception in the CTd plots at 0830 when the sun was East South East and at an elevation of approximately 30^0. The largest rectangle represents the 3 by 4 m cell with a grevillea tree at each corner.

which has important implications for the modelling of light interception (cf. Section 7.9) and for the estimation of canopy cover for modelling rainfall interception.

Interception of rainfall by the trees was not estimated during the 1992/3 short rains due to the smaller size the tree canopy and the consequently much smaller canopy storage component (leaf area index in Td was < 0.1 for much of the 1992/3 season compared to >1 by the end of the 1993/4 short rains); I_t probably accounted for <1 % of the seasonal rainfall during the 1992/3 short rains. Interception of rainfall by the crop was not measured at this site, but would be expected to be much smaller than that by the trees (cf. Section 7.9).

7.8 WATER BALANCE

1992/3 short rains

Total rainfall during the 1992/3 short rains was more than double the seasonal average at a time when the grevillea trees were small, and had a correspondingly low water use. Figure 7.27a shows the estimated seasonal water balances for the CTd, Cg and Td treatments. The dominant component of the water balance was soil evaporation (47 %), with transpiration being a minor component (4 - 6 %). The drainage term was calculated as the residual rainfall unaccounted for by the other components and would have included interception by the crops and small trees. However, the substantial size of D_r (>300 mm) indicates why tree transpiration was able to continue unabated during the dry season.

1993/4 short rains

In contrast to the previous short rains, rainfall was approximately 20 % below the long-term seasonal average. The dominant component of the water balance was again soil evaporation (53 - 61 %; Fig. 7.27b), but water use by the trees and crops accounted for a much greater proportion of total water losses (16 - 19 and 9 - 16 % respectively), with less than 5 % of the water balance being attributed to drainage in the CTd treatment. In this drier season,

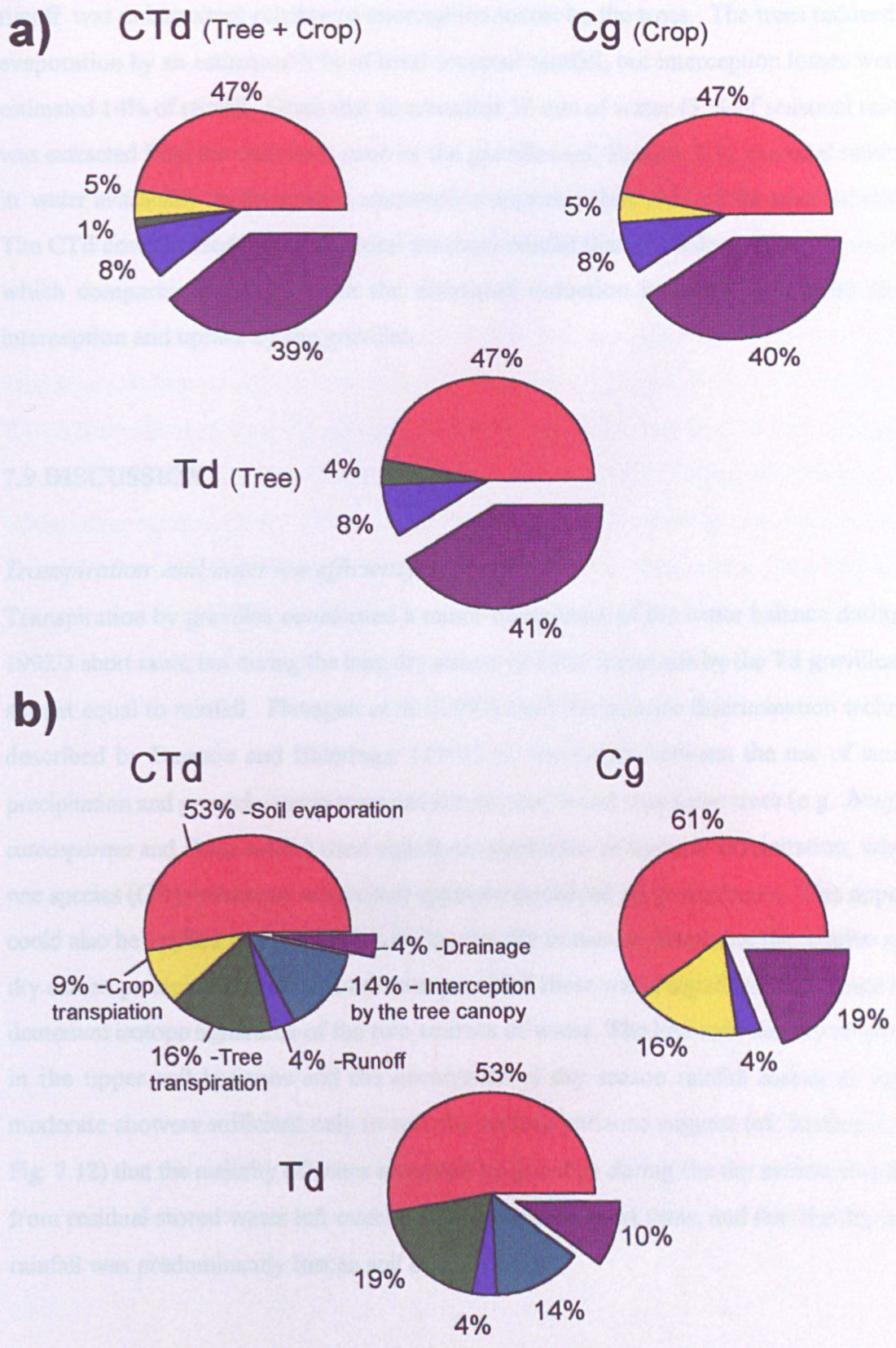


Figure 7.27 Water balance for the CTd, Td and Cg treatments during (a) the 1992/3 short rains and (b) the 1993/4 short rains. Drainage was estimated as the residual water not accounted for by the other components and includes storage, deep percolation and lateral flow.

runoff was unimportant relative to interception losses by the trees. The trees reduced soil evaporation by an estimated 8 % of total seasonal rainfall, but interception losses were an estimated 14% of rainfall. Given that an estimated 12 mm of water (3 % of seasonal rainfall) was extracted from the crop root zone by the grevillea (cf. Section 7.3), the total reduction in water availability to the cowpea amounted to approximately 9 % of the seasonal rainfall. The CTd cowpea used less of the total seasonal rainfall than the sole cowpea (9 vs. 16 %) which compares favourably with the estimated reduction in water availability due to interception and uptake by the grevillea.

7.9 DISCUSSION

Transpiration and water use efficiency of grevillea

Transpiration by grevillea constituted a minor component of the water balance during the 1992/3 short rains, but during the long dry season of 1993 water use by the Td grevillea was almost equal to rainfall. Flanagan *et al.* (1992) used the isotopic discrimination technique described by Dawson and Ehleringer (1991) to distinguish between the use of summer precipitation and groundwater in trees and shrubs, and found that some trees (e.g. *Juniperus osteosperma* and *Pinus edulis*) used significant quantities of summer precipitation, whereas one species (*Chrysothamnus nauseosus*) appeared to depend on groundwater. This approach could also be applied to the grevillea during the dry season to determine the relative use of dry season precipitation and groundwater provided there was a significant difference in the deuterium isotope signatures of the two sources of water. The low root density of grevillea in the upper soil horizons and the occurrence of dry season rainfall mainly as light to moderate showers sufficient only to wet the surface horizons suggest (cf. Section 7.3 and Fig. 7.12) that the majority of water absorbed by grevillea during the dry season was drawn from residual stored water left over from the previous short rains, and that the dry season rainfall was predominantly lost as soil evaporation.

The use of D_e, as opposed to mean daytime D reduced the proportional differences between the values of e_wD_e for grevillea for the different seasons (cf. Section 7.2). The remaining difference possibly originated from several factors. For example, during the 1992/3 short rains, the young grevillea saplings may have been investing a larger proportion of their photosynthetic products in root growth than in subsequent seasons, with the result that W was substantially underestimated. The young grevillea trees were effectively isolated from each other at this stage and their canopies were relatively sparse (leaf area index « 0.1) as compared with those present twelve months later (leaf area index c. 1). During the 1994 long rains (the season immediately following this study), Wallace *et al.* (1995) measured D 15 cm above ground level, above the tree canopy and in the middle of the tree canopy and reported that conditions were "consistently cooler and wetter" at canopy level than at either of the other two locations. This microclimatic modification by the larger grevillea is likely to have substantially reduced the D values experienced by the tree canopy, thereby reducing e_wD_e during the 1993/4 short rains, and to a lesser extent in the preceding seasons. Further research is necessary to determine whether the water use efficiency of the cowpea was significantly affected by the presence of the trees.

Green *et al.* (1989) used the heat pulse technique to measure night-time transpiration in kiwi fruit and apple trees and found that transpiration increased with saturation vapour pressure deficit; night-time transpiration accounted for 19 and 6 % of total daily transpiration in these species. It is therefore possible that the omission of night-time transpiration by grevillea from the calculations reported here resulted in some underestimation of water use. However, the prevailing night-time saturation vapour deficits at the site were consistently <0.3 kPa and the atmosphere remained close to saturation for much of the night (Wallace *et al.*, 1995), suggesting that night-time transpiration would have been low; this supposition is supported by evidence provided by Khan and Ong (1995) who used heat balance gauges and gravimetric methods to measure transpiration in potted grevillea trees and found that night-time transpiration was negligible.

Harwood (1992b) described grevillea as being "facultatively deciduous" since it sheds leaves during severe drought. The natural distribution of grevillea covers an estimated range of mean annual precipitation extending from 720 to 1710 mm; Machakos is at the lower end of this range and the failure of the 1993 long rains might have been expected to have limited growth. However, the exceptionally high rainfall of the 1992/3 short rains permitted continued tree growth through the dry period up until the beginning of the following short rains. Reich and Borchert (1988) showed that stomatal control of water loss declined with increasing leaf age in rainforest trees with long-lived leaves, and that the large plant water deficits which developed during dry periods promoted leaf senescence and shedding. The observed depression of transpiration in grevillea during the afternoon towards the end of the 1993/4 short rains (Fig. 7.9b) in the absence of detectable leaf wilting suggests that stomatal control was well maintained in the grevillea. However, these observations were made after a period of rapid leaf development when many of the leaves were only a few weeks old; it is possible that in seasons with a differing rainfall distribution at the same site, for example, a prolonged dry period following an average rainy season, leaf shedding would be observed.

Excavation of grevillea root systems

The results obtained demonstrate that excavation to a depth of 60 cm was sufficient to remove the crop rooting zone for cowpea and support the view that grevillea is predominantly deep rooted, even in relatively shallow soils (cf. Section 7.3). This deep rooting habit enabled transpiration to be maintained following excavation at around 70 % of the unexcavated values for 10 month old trees and at 70-80 % of the excavated control for 16-17 month old trees with their more extensive root systems (Fig. 7.14).

Although it is possible that grevillea roots extending below 60 cm were able to compensate for the excavation and exposure of the surface roots in a similar way to the croton tree examined by Ong and Khan (1993; cf. Section 1.5), certain considerations suggest that little or no such compensation occurred. For example, when adjacent grevillea trees were pruned while sap flux was being measured, the lack of any significant decrease in sap flux after a

substantial reduction in leaf area suggested that sap flux was supply-limited rather than demand-limited. In addition, the two trees which had deep roots severed during excavation exhibited a reduction in sap flux approximately proportional to that in root cross-sectional area and showed no apparent compensation in water uptake by the remaining roots (Table 7.3).

These results suggest that there is substantial below-ground complementarity between grevillea and cowpea, although in seasons of low rainfall even the relatively modest uptake of 15-30 % of the total water requirements of grevillea from within the rooting zone of cowpea is likely to reduce crop yield. However, limited competition may be a small price to pay for a greatly increased resource capture and overall system productivity. Appropriate management practices may be used to minimise competition between trees and crops in agroforestry systems; for example, pruning the lateral roots of grevillea has been shown to reduce competition for water with intercropped maize (van Roode, 1992), although this is rarely a viable practice for farmers lacking mechanised technologies. However, it may be possible to identify other provenances of grevillea or other species in which an even greater proportion of the resources required are captured at depth, providing more complete below-ground complementarity.

The combination of sap flux measurements and excavation to determine the extent of below-ground complementarity provides a more direct, dynamic and precise method than alternatives such as neutron probes, which cannot distinguish between uptake by the tree and crop roots. However, the method outlined here is both destructive and labour-intensive, and is best used in conjunction with other approaches. The 60 cm excavation depth used here was close to the maximum excavatable depth at this site, and the procedure was complicated by the hard gravelly nature of the soil. If a similar approach was applied to deeper rooting crops such as maize, it would be preferable to use sites with deeper, more easily removable soil to facilitate excavation of the crop rooting zone. The method could be used in conjunction with the approach described by Ong and Khan (1993), in which heat balances

gauges were used to determine the sap flux through individual lateral roots to establish whether the trees compensated for the excavation of their surface roots by increasing abstraction at depth and hence sap flux from the deeper roots. Alternatively, measurements made before and after pruning the canopy could be used to establish whether sap flux was supply or demand-limited. In large trees with extensive lateral root systems, the approach of Ong and Khan (1993) has obvious advantages due to the large volume of soil that would have to be excavated.

Soil evaporation

Although the Ritchie model (Ritchie, 1972) provides a simple and useful approach for estimating soil evaporation, it is perhaps over-simplistic and the basic assumption of two-stage soil evaporation may not always be correct. It is likely that moderate rainfall onto a very dry soil will be readily absorbed and little first stage evaporation will take place. However, when the soil is saturated and at or above field capacity in the surface horizons, then modest rainfall may result in first stage evaporation over prolonged periods. The square root of time approach adopted by Ritchie appears to provide reasonably reliable in estimates during this phase, pending the development of more precise models (cf. Section 7.5 and Fig. 7.15). Microlysimeters offer a cheap, replicable method for measuring soil evaporation, although the imposition of a no-flow barrier at their base prevents the accurate determination of soil evaporation when periods of several days have elapsed following rain. Wallace (1996) suggested that, when second stage evaporation has been completed, third stage evaporation is limited by the rate of diffusion of water vapour through the soil column, and is of little consequence in most agroforestry systems since it will constitute a negligible part of the overall water balance. However, where there are prolonged dry periods, as in most of the semi-arid tropics, the relative importance of third stage evaporation needs to be determined, perhaps using the micro-Bowen technique of Ashktorab *et al.* (1989), or alternatively using large, high-resolution lysimeters which are sufficiently deep to be representative of the soil profile.

The effect of shade on soil evaporation provides some cause for optimism (Figs. 7.21 and 7.22). Wallace *et al.* (1995) measured soil evaporation in the dispersed tree treatment of CIRUS and proposed a Ritchie model similar to that employed here. However, their model for soil evaporation under shade assumed that first stage evaporation occurred for two days and assigned values of 3.13 and 4.38 for parameters U and □; these assumptions would have led to predicted soil evaporation values which were greater on the third day after re-wetting the soil than on the previous two days, an unlikely occurrence. If soil evaporation enters the second stage when capillary flow breaks down near the soil surface, this phase would be hastened by high evaporative demand and potentially prolonged by shade or low temperatures, low net radiation or low saturation deficits. However, under the patchy shade that occurs under sparse tree canopies, the shaded areas may be subject to substantial advection, with the result that there may be little reduction in soil evaporation. The impact of shade on soil evaporation is clearly an area in need of further research.

The results obtained show that mulching did not significantly affect soil evaporation and may even have increased evaporation at the intermediate mulching rate (2.25 t ha^{-1}, Fig. 7.21). Budelman (1989) has previously observed that a high application rate (5 t ha^{-1}) of leaf mulch from three tree species significantly reduced soil temperature and increased soil moisture levels in the top 5 cm of the soil. Although these results might suggest at first sight that soil evaporation was reduced, it is entirely possible that the effect of the mulch was to prevent capping of the soil, making it impossible to assess the impact on soil evaporation *per se*. Hadrich and Heuveldop (1978) found that soil evaporation accounted for 18 % of the annual rainfall within a larch forest, as compared to 15 % in the open. The litter on the forest floor intercepted 37 % of the rainfall received and was responsible for the greater soil evaporation component within the tree stand. Thus, at low to moderate application rates, the mulch may simply serve to absorb some of the rainfall which is subsequently readily evaporated, whilst failing to alter substantially the boundary layer conditions of the soil; the mulch may effectively provide a large surface area for evaporation. High mulching rates providing near-complete ground cover may reduce direct evaporation from the soil, but evaporation from

the mulch itself might well outweigh this saving depending on the degree of rainfall interception and the structure of the mulch. An ideal mulch for reducing soil evaporation might be one which is rich in waxy leaf material with a low uptake capacity for moisture, combined with a high albedo to reduce net radiation at the soil surface. Thus, although the incorporation of organic matter into the soil may have potential benefits, the application of green manures and mulches is not a universal panacea for problems of soil moisture conservation.

Interception

Rainfall interception by agroforestry systems has been the subject of few experimental studies, with far greater emphasis being given to the interception of light. What research that has been done indicates that interception losses may be substantial, with approximately 20 % of total annual rainfall being intercepted by the tree component of a leucaena /millet agroforestry system at Hyderabad, India (Monteith *et al.* 1991). The value of approximately 14 % for rainfall interception by the dispersed grevillea trees during the 1993/4 short rains indicates that total interception losses may approach transpiration by the woody component of agroforestry systems (cf. Section 7.7). While water used for transpiration by the trees may be extracted from beneath the crop roots in a non-competitive way, the interception of rainfall represents a potentially serious loss of available water to the crop. The distribution of throughfall appeared to affect crop yield in both the row-planted CTa (Fig. 7.22) and dispersed-planted CTd (Fig.7.25) treatments. Rainfall interception by the cowpea was probably negligible because of its smooth leaves with drip tips and low leaf area index for much of the growing season.

In areas such as Machakos where rainfall occurs chiefly at night, a simplified Gash model may be parameterised using the approach of Teklehaimanot and Jarvis (1991; cf. Section1.5) to establish the crown storage capacity for a range of tree sizes. This might be achieved on a small scale by using severed branches rather than whole trees. Total rainfall interception for a given tree stand of known size class could then be calculated using a simplified version

of the Gash equation, with evaporation during periods of rainfall being ignored. In areas where rainfall occurs during periods of high evaporative demand, and particularly where the mean rate of rainfall is low, evaporation during rainfall cannot be neglected.

Although Monteith *et al.* (1991) suggested that the kinetic energy of rainfall is dissipated during the interception process, there is also evidence that the coagulation of rain into larger drops may increase rather than decrease the kinetic energy of the rain drops (Bussiere, 1995). This has potentially important consequences for the erosivity of the rain, direct mechanical damage to crop plants and the spread of fungal pathogens.

Runoff

Estimated runoff during the 1992/3 short rains and measured runoff during the 1993/4 short rains accounted for <9 % and <4 % of the total seasonal rainfall (cf. Section 7.6). At sites such as Machakos, runoff is substantial only when seasonal rainfall is high and water is not a limiting factor for crop growth. Kiepe (1995) reported that mulching and contour-planted hedgerows both significantly reduced runoff. On a separate trial at Machakos, the mulch was completely washed away during a large storm event during the 1992/3 short rains, at a time when it might have been expected to offer maximum protection against runoff (unpublished results); thus there is clearly a limit to the protection that can be provided against runoff and erosion by mulching. At sites such as Machakos, such strategies are likely to be of limited value and may be of greater importance on soils with very poor infiltration characteristics.

Summary

During both short rains, soil evaporation proved to be by far the largest component of the water balance in all treatments, and less than 6 % of the total seasonal rainfall received during the 1992/3 short rains was captured by the trees and crops in all treatments. However, the continued extraction of water by the trees during the following dry season greatly increased resource capture; total water uptake was three times greater in the sole

trees than in the sole crop when water use during the dry season was included. During the 1993/4 short rains, water use was greatest in the CTd treatment, in which 25 % of the total seasonal rainfall was used by the trees and crops. Total transpiration by the CTd trees exceeded the interception losses, but approximately 70 - 85 % of the transpired water was apparently drawn from beneath the crop root zone; interception losses may therefore have had a greater effect on crop growth by more substantially reducing the quantity of water available to the crop.

CHAPTER 8

FINAL DISCUSSION

The results of both trials reported in this thesis are discussed here in terms of the interactions which govern productivity and the implications for agroforestry, particularly in the semi-arid tropics. A discussion of the results of both trials is presented first, followed by the implications for light capture and utilisation and the components of the water balance in agroforestry systems. Recommendations for tree and crop selection, the design of agroforestry systems and future research priorities are also discussed.

8.1 ABOVE AND BELOW GROUND COMPETITION

The leucaena/maize systems described in Chapters 2 and 3 showed substantially increased capture of both light (25 %; Table 3.1 and Fig. 3.1) and water (100 %; Fig. 3.5) when upperstorey trees were combined with maize (LM treatment) as compared to sole maize. Seasonal rainfall during the 1992 long rains was 237 mm, 30 % below the long-term average, and water use by the sole maize accounted for an estimated 64 mm, almost 30 % of the seasonal total. However, most of the resources in the LM treatment were captured by the upperstorey leucaena, which was less efficient in terms of resource utilisation than the understorey C4 maize. Competition for light and water were estimated to be responsible for approximately equal reductions in the yield of the LM maize (c. 30 % for each of these variables; Fig. 3.2). The application of irrigation to the upperstorey trees and crops (LMI) largely removed competition for water, but the consequent increase in the growth of the tree canopy resulted in more extensive competition for light, with the result that maize yields were approximately half of those for the irrigated sole maize control (SMI; cf. Table 3.2).

The continued water use during the dry season by the LM leucaena, while initially suggesting temporal complementarity, may well have increased below-ground competition for water with maize during the following rainy season. The lack of an appropriate sole tree control did not allow land equivalent ratios to be determined, but

the substantial reductions in the yields of maize in the LM and LMI treatments (Table 3.2) suggest that the two components would have performed better if grown separately. Corlett (1989) and Corlett *et al.* (1992a, b) came to the same conclusion for a leucaena/millet (*Pennisetum typhoides*, also a C4 crop) agroforestry system in semi-arid India. The leucaena was grown in double rows with a 0.5 m intra-row spacing to provide hedgerows separated by 2.8 m wide alleys, while the millet was planted at a 0.47 by 0.15 m spacing during two consecutive annual rainy seasons commencing when the leucaena was approximately 12 months old. Although the leucaena was pruned to a height of 65-70 cm prior to and during the first rainy season, rapid canopy growth allowed the leucaena to attain a maximum height approximately 1 m greater than the millet, with near complete closure of the canopy occurring during the latter part of the season (c. 67 DAS). The alley cropped millet exhibited yield reductions of 46 and 82 % in consecutive rainy seasons, with most of this loss being attributable to shade from the leucaena in the first season and a combination of shade and reduced fractional interception of available radiation by millet during the second season. The reduced fractional interception by millet during the second season was probably the result of more extensive below-ground competition from the older, better established root system of leucaena; Corlett's root barrier treatment (comprising a polythene barrier installed to a depth of 50 cm to separate the roots of the trees and crops) demonstrated a significant role for below-ground competition.

In the ABG trial, the grain yield of maize in the unirrigated hedgerow treatment (HM) was 18 % lower than in the sole crop, an effect largely attributable to competition for water. However, the maize in the irrigated hedgerow treatment (HMI) moderately, but not significantly ($p > 0.05$), out-yielded the irrigated sole maize (9 % greater; Table 3.2). Although the maize was planted at the recommended density for the Machakos climatic region, it is possible that the adoption of a higher population in the irrigated sole maize might have significantly increased maize yields. The HMI maize, may or may not have significantly out-yielded irrigated sole maize planted at a higher population but, if the yield increase was the result of nitrogen input from the leucaena roots rather than due to chance, the increase in yield might have been maintained.

Gutteridge (1988) grew kenaf (*Hibiscus cannibinus*) as sole crops with a 50 cm inter-row spacing both with and without nitrogen fertilizer, and also in unfertilized 3 and 5 m wide alleys separated by hedgerows of leucaena on a low-fertility ultisol soil in south-eastern Queensland. The leucaena was coppiced to a height of 25 or 50 cm two or four times per season and the cuttings were returned to the alleys as mulch. No significant difference between the yields of alley-cropped kenaf and the unfertilized control was observed until the third season, when yield was 25-40 % greater in the alley crop; yields were nevertheless consistently greater in the fertilized kenaf plots than in the alley crop. Rainfall was over 800 mm during the third season and supplementary irrigation was applied during the post-rains period. These results suggest that leguminous tree species such as leucaena have a limited ability to sustain moderate crop yields on low fertility sites where light and water are not limiting; a similar conclusion has been reported for maize/leucaena alley crops in Nigeria (Kang, 1981) and western Kenya (Heineman, 1995).

8.2 COMPLEMENTARITY OF RESOURCE USE ON SLOPING LAND

In the grevillea/cowpea systems described in Chapters 4-7, overall resource capture was greatest in the tree/crop mixture, as for the leucaena/maize system. During the 1992/3 short rains, the cowpea in the dispersed tree plus crop treatment (CTd) experienced an estimated 4 % shade, with no apparent effect on crop yield. Shade trials showed that there was no significant reduction in cowpea yields until shading intensity reached 75 % (Fig. 6.8). During the 1993/4 short rains, mean seasonal shade levels in the CTd treatment exceeded 50 % only over a small area (approximately 5 % of the cell; Fig. 6.9, Section 6.4) and the seasonal mean for the entire cell was 31 %; given the shade tolerance of the cowpea and the moderate shade imposed in the CTd plots, light may be regarded as non-limiting and the direct effects of shade as being negligible. In the latter season, the combined seasonal light interception for the CTd trees and crops was 25 % greater than that for sole trees and more than double the value for sole cowpea (Fig. 6.7).

During the 1992/3 short rains, rainfall was more than double the seasonal average at 766

mm, and total water use by the trees and crops was estimated to be 6 % or less of the total rainfall in all treatments, with the CTd trees using only approximately 1 % (Fig. 7.27a). However, during the ensuing short rains when rainfall was 20 % below average (280.5 mm), water use by the CTd and Cg cowpea accounted for an estimated 9 and 16 % of rainfall, with the CTd and Td trees using approximately 16 and 19 %. During this season, the grevillea canopies were much larger than during the preceding short rains, and the seasonal mean values for fractional interception by the CTd and Td trees increased from 0.04 and 0.10 during the 1992/3 short rains to 0.31 and 0.29 during the 1993/4 short rains.

There was apparently substantial below-ground complementarity between the grevillea and associated crops. For example, cowpea roots were largely confined to the upper 60 cm of soil and the experiments involving excavation of the grevillea root systems established that the trees were capable of meeting 70-80 % of their transpiration requirements from below this depth; the proportion of the grevillea root cross-sectional area ending below 60 cm was positively correlated with the proportion of transpiration maintained after excavation (Eq. 7.4). However, despite the shade tolerance of cowpea and the observed below-ground complementarity, CTd cowpea yields during the 1993/4 short rains were > 60 % lower than in the sole crop.

Interception losses by the CTd grevillea canopy comprised an estimated 14 % of the seasonal rainfall, and probably accounted for much of the observed reduction in CTd cowpea yields. The estimated distribution of intercepted rainfall within the plots by the CTd grevillea (Fig. 7.25) was closely reflected by the pattern of cowpea grain yield (Fig. 5.13), indicating the potential importance of interception losses. The tree rows in the CTa treatment were aligned perpendicularly to the prevailing wind (Figs. 7.22 and 7.23) and the depression of crop yield was significantly greater (equivalent to 17 % of the sole crop yield) at distances of up to 3.5 m from the tree row on the downwind side of the tree rows than at the corresponding upwind location (Fig. 7.22); this additional yield loss, although statistically significant, was equivalent to only 1 % of seasonal rainfall in terms of crop water use. The row yields of the CTa and CTc cowpea, expressed relative to the sole crop yield, were positively correlated ($r^2 = 0.92$, $n = 15$) with increasing distance

from the tree rows (Fig. 5.12), and interpolation using a linear regression model suggested that yield directly under the tree rows would be approximately 40 % of that in the sole crop, with yields equivalent to the sole crop yield only being reached at distances >5 m from the tree rows. The observed yield depression is likely to have been due to a combination of below-ground competition for water and rainfall interception near to the trees, and to interception alone at greater distances since the rooting studies had demonstrated that the lateral spread of the grevillea roots was limited (Fig. 7.12).

During the 1993/4 short rains, the land equivalent ratio was still significantly greater than 1 in the CTd treatment (Fig. 5.14) because of the substantial biomass production by grevillea, which was similar to that of the sole trees; hence the cowpea yield, although only c. 40 % of the control value, might be regarded as a benefit if the tree and crop products were of similar value. As row-planted grevillea trees were grown at a sub-optimal density and therefore their biomass production during the 1993/4 short rains was lower than in the dispersed tree treatments, for which the values in the CTa and CTc treatments were 65 and 57 % of those for the sole trees. However, the reduction in cowpea yields in the row-planted treatments was less than in the CTd treatment, at approximately 60 % of the sole crop, and the LER values were still above 1. Grain yields for cowpea were negatively correlated ($r^2 = 0.84$, n = 10) with the product of grevillea biomass production and the proportion of the plot with a soil depth less than the mean soil depth for the entire experimental site (P_s; cf. Section 4.5 and Fig. 5.10). Multiple regression analysis of cowpea yield against P_s and grevillea biomass production accounted for 85 % of the variation in crop yield (Eq. 5.1; Fig. 5.11). Indicating that the availability of below-ground resources to cowpea decreased as soil depth decreased and grevillea yield increased; increases in grevillea yield would have been accompanied not only by increased below-ground competition but also by increased rainfall interception resulting from the greater aerial biomass of the grevillea. The validity of LER values greater than 1 depends on the sole crops and trees being grown at their optimal densities (Loomis and Connor, 1992); thus sole grevillea could have been grown productively at a higher density up to the end of the first short rains. However, the slight decrease in transpiration during the 1993 dry season (Fig. 7.5) indicates that water was becoming limited and therefore that higher densities of grevillea might well have increased intra-

specific competition without increasing overall stand biomass. A higher initial planting density, followed by thinning of the trees after 15 months, whilst possibly increasing the biological yield, would have little economic justification.

Tyndall (1993) reported that the average number of grevillea trees on small farms (average size 1.8 ha) in the Kirinyaga area of Mount Kenya was 55, and that these were primarily boundary-planted in double or single rows, with the result that their overall density was approximately 30 trees ha^{-1}. Similarly, in coffee plantations, grevillea was often randomly spaced at 10 - 20 m intervals to provide 5 - 100 trees ha^{-1} (Spiers and Stewart, 1992), compared with over 800 trees ha^{-1} in the dispersed tree plots of CIRUS. However, in the survey conducted by Spiers and Stewart (1992), 13 % of farmers planted grevillea in small woodlots at a 2.5 - 3.0 m spacing, and these were frequently intercropped until canopy closure occurred; the resulting tree density of 1100 - 1600 trees ha^{-1} is substantially higher than in the CTd plots, but rainfall in the Embu and Meru districts is considerably greater than in Machakos (900-1500 mm vs. 750 mm), with the result that higher densities of grevillea are potentially feasible. Kerkhoff (cited by Ongugo, 1992) found that, when grevillea was interplanted with maize and beans in Rwanda, the maximum combined yield was obtained with a population of 400-600 trees ha^{-1} after 4-6 years and 250-300 trees ha^{-1} after 9-10 years, with the canopy cover provided by the trees being c. 20 % in both cases; these values are significantly lower than the c. 30 % canopy cover provided by the CTd treatment during the 1993/4 short rains.

The competitive interactions between the tree and crop components of the agroforestry treatments altered substantially with time; for example, seasonal above-ground dry matter production values for grevillea and cowpea (maximum dry weight rather than final harvest for cowpea) were 0.3 and 1.7 t ha^{-1} during the 1992/3 short rains, compared to 3.2 and 1.0 t ha^{-1} during the 1993/4 short rains. Crop production in the agroforestry treatments was apparently limited by competition for water with grevillea during the 1992/3 short rains, when the seasonal rainfall was 20 % below average; the CTd cowpea would have required only an extra 7 % of the seasonal rainfall to achieve the sole cowpea yield provided the water use:dry matter ratio was comparable for the sole and intercrop.

Thus, if the seasonal rainfall had been near-normal, there might have been little or no yield reduction in cowpea. Pre-season pruning of the grevillea might well reduce interception losses and below-ground competition with associated crops, but would also be expected to reduce the growth of grevillea. Spiers and Stewart (1992) reported that two-thirds of farmers surveyed in the Meru and Embu districts of Kenya carried out annual pruning or pollarding of grevillea, not only to reduce competition with associated crops, but also to increase timber quality and provide poles and fuelwood.

There was sufficient evidence of below-ground complementarity between grevillea and cowpea to suggest that these species may be grown together successfully if both are desired by the farmer. Pruning the trees, while leading to biologically sub-optimal tree yields, may permit a combination of higher crop yields and the production of firewood, fodder or mulch and higher quality timber. The density of the grevillea should be adjusted depending on the principal component required; if this is timber or fuelwood, then a similar density to the CTd plots would be beneficial, although this would be achieved at the expense of reduced legume yields in drier than average rainy seasons. However, if the tree crop is of secondary importance, then a lower density or boundary planting arrangement may be preferable.

8.3 CIRUS AND THE ABG TRIAL COMPARED

Although the ABG and CIRUS trials were located less than 500 m apart, they differed substantially in terms of soil characteristics. The ABG trial was located on a moderately fertile river terrace, on which soil depth was consistently greater than 1.5 m, whereas the mean depth in CIRUS was <75 cm. These soil properties were reflected by the sole maize yields obtained during the 1992 long rains of 1.2 and 3.2 t ha^{-1} for CIRUS and ABG respectively.

Table 8.1 compares various biophysical values determined in the ABG trial during the 1992 long rains and in CIRUS during the 1993/4 short rains. Although rainfall during the former season was 17 % lower than in the latter (237 vs. 286 mm), the sole maize in the

ABG trial attained a maximum fractional interception of PAR of 0.67, with a seasonal mean value of 0.38, which was greater than that for any other single component in either trial. Cereal canopies, due to their rapid leaf initiation and expansion, may achieve higher seasonal fractional interception values than many C3 crops. However, mean global radiation was only 15 MJ m^{-2} d^{-1} during the 1992 long rains, compared with 22 MJ m^{-2} d^{-1} during the 1993/4 short rains. Thus, CTd grevillea had a higher S_p value than maize despite its lower seasonal mean fractional interception. The corresponding S_p value for leucaena was only 63 % of that for grevillea even though the equivalent f_p value was only 10 % lower.

Table 8.1 Comparison of above-ground dry matter (W, g m^{-2}), seasonal mean and maximum fractional interception of PAR (f_p), total PAR interception (S_p, MJ m^{-2}), dry matter:radiation use coefficient (e_p, g MJ^{-1} PAR), transpiration (Et, mm), and the product of the dry matter:water use coefficient and mean daytime saturation vapour deficit (e_wD, g kPa kg^{-1}) in the ABG and CIRUS trials.

	ABG			CIRUS		
	SM Maize	LM Maize	LM Leucaena	Cg Cowpea	CTd Cowpea	CTd Grevillea
W	651	288	264**	198*	111*	263
Mean f_p	0.38	0.21(0.28)	0.28	0.19	0.15(0.10)	0.31
Max f_p	0.61	0.31(0.42)	0.30	0.42	0.22(0.33)	0.45
S_p	263	132	200	149.9	80	319.7
e_p	2.48	2.18	1.32**	1.32	1.39	0.82
Et	64	27	100	47.2	26.5	45.7
e_wD	8.74	-	2.27	-	-	5.7

*W values for cowpea represent maximum dry weight rather than that at final harvest.
**e_p was derived from data presented by Corlett (1989) and was used to estimate dry matter production.
NB. Values in parenthesis represent the fractional interception of PAR incident on the crop canopy (i.e. the proportion of the PAR transmitted by the tree canopy that was intercepted by the crop).

Light capture and conversion to dry matter

The e_p value derived from Corlett's (1989) e value for total solar radiation for leucaena was over 50 % greater than that for grevillea, and might therefore have resulted in an overestimation of dry matter production in leucaena. Two factors suggest that the difference in e_p values between the tree species was genuine; firstly, the lower mean daily solar radiation during the 1992 long rains would have been expected to reduce the frequency and extent of light saturation of photosynthesis in the leucaena and, secondly, photosynthesis is strongly dependent on nitrogen status (Loomis and Connor, 1992). Thus, the leguminous leucaena might be expected to have a higher foliar nitrogen content than grevillea when grown on low fertility soil. Further evidence to support this view is that the e_p value used for leucaena was closely comparable to the e_p value calculated for the leguminous sole cowpea.

Water use and conversion to dry matter

In a survey of the literature on water use in intercropping, Morris and Garrity (1993) found that water availability was the main determinant of water use and that water use by intercrops ranged between -6 and 7 % of that in the corresponding sole crop in all but two of the ten studies reported. However, in CIRUS during the 1992/3 short rains, water use in the CTd agroforestry treatment was over 50 % greater than in either of the sole tree or crop treatments. Similarly, the ABG upperstorey leucaena and maize system captured twice as much water as the sole maize.

The e_wD values for grevillea were more than double those for leucaena, for which there are several possible explanations (Table 8.1). The heat balance gauges were calibrated for grevillea and a correction factor was found to be necessary for stems over 32 mm in diameter (Eq. 4.18). If a similar situation applied for leucaena, for which the average stem diameter was 55 mm (s.e. 8.6), water use may have been overestimated by 25 % and e_wD would have been over 3 g kPa kg^{-1}. However, two factors support the low value obtained for e_wD in leucaena: firstly, dry matter:water use ratios tend to be lower in legumes than in other C3 plants because of the high metabolic cost of supporting the nitrogen-fixing symbionts (Ong *et al.*, 1996); secondly, transpiration by leucaena appeared to be demand-driven, with little stomatal control and maximum rates of

transpiration coinciding with periods of maximum saturation vapour deficit (cf. Figs. 3.6 and 7.9b), with a consequent reduction in e_w. The apparent difference in the extent of stomatal control between the two species may be a consequence of their differing phenologies; leucaena has been observed to lose most or all its leaves during the dry season, whereas grevillea retains much of its canopy except during prolonged drought (Harwood, 1992). Reich and Borchert (1988) examined changes in stomatal function with leaf age in several tropical tree species and concluded that stomatal control was most effective in evergreen species which continue to grow during drought, and least effective in deciduous species which shed their leaves during the dry season; thus, it is possible that grevillea possesses significantly greater stomatal control than leucaena.

Rooting density in the upperstorey leucaena was greatest in the upper 50 cm of the soil profile, with some roots extending to depths exceeding 2.5 m, whereas the roots of hedgerow leucaena were confined to the upper 2 m of the soil profile (Govindrajan *et al.*, 1996). Thus, there was considerable below-ground competition between the leucaena trees and hedgerows and the associated maize. In contrast, the root excavation experiments with grevillea revealed a predominantly deep rooting habit (Fig. 7.12) and the ability to extract as much as 80 % of its water requirements from beneath the cowpea rooting zone (Fig. 7.14). Thus, grevillea exhibited the potential for substantial below-ground complementarity with shallow-rooted crops such as cowpea.

C4 crops in agroforestry

In the above and below-ground competition trial, the 30-50 % reduction in maize yields which resulted from shading by the upperstorey leucaena indicates that the potential for combining upperstorey trees with C4 understorey crops is strictly limited (Table 3.2). McPherson and Slatyer (1973) suggested that the imposition of any shade on a C4 crop would reduce carbon fixation unless photosynthesis was already limited by partial stomatal closure. This conclusion was supported by Lott (pers. comm.) who found that maize subjected to 25 % artificial shade provided by neutral density shade nets outyielded the surrounding water stressed sole crop; as the latter experienced water stress due to low rainfall the addition of trees would be expected to further exacerbate this condition. This presents an interesting dilemma for agroforestry systems involving mixtures of

upperstorey trees and C4 crops, since the only time when shade will not reduce dry matter production by the understorey crop is likely to be when it is water stressed; under such conditions, water extraction by the upperstorey trees is likely to exacerbate any such stress. Conversely, when water is non-limiting for the growth of understorey C4 crops, any shading may reduce growth. Temporal complementarity is likely to provide a better option for combining trees and C4 crops, where the tree canopies are maintained out of synchrony with the crop either by their phenology or the imposition of planned pruning regimes. Monteith *et al.* (1991) reported that a 4 by 4 m spacing of *Faidherbia albida* intercepted a maximum of only 20 % of the incident radiation and that this species sheds all of its leaves prior to the rainy season, with the next flush of leaves developing during the latter part of the rainy season; this species therefore exhibits substantial temporal complementarity with a rapidly developing cereal canopy. Thus *F. albida* would be expected to cast comparatively little shade on understorey crops, thereby providing at least a partial explanation for why naturally occurring *F. albida* trees in West Africa are commonly underplanted with maize with apparently beneficial effects;. However, there is some evidence to suggest that substantial quantities of nitrogen may be released by *F. albida*, which could be an additional reason for the adoption and success of this practice (ICRAF, 1992).

C3 crops in agroforestry

As previously stated, when subjected to 25, 50 or 75 % artificial shade at Machakos, cowpea showed no significant decrease in yield except under the highest shade level (Fig. 6.8). A similar experiment with field bean (*Phaseolus vulgaris*) showed no reduction in yield under 33 % shade, whereas yield reductions of 37 and 56 % were induced under 58 and 82 % shade (ICRAF, 1993). As the latter trial was fully fertilized and irrigated, the limiting resource would have been expected to be light, although population density may have been a limiting factor since the beans were planted at the optimal density for rainfed agriculture in the Machakos region and were therefore probably unable to reach a sufficiently high LAI to achieve maximum light capture under these unusually favourable conditions of water and nutrient availability. Given the response of C3 plants to increasing radiation, with maximum photosynthetic rates being reached at moderate radiation levels (Fig 1.7a), the beans would have frequently reached light saturation for

photosynthesis. Thus, moderate shade did not affect yield and Keating and Carberry's (1993) theory that spatial complementarity for light utilisation may only be expected when the optimal sole crop density does not result in full light interception, due to limitations of water or nutrient availability, was not properly tested because of the probable sub-optimal crop density adopted in this experiment. However, Keating and Carberry's theory appears to have been vindicated in CIRUS when, during the 1993/4 short rains, fractional interception of PAR reached a maximum of <0.5 in the sole cowpea and the total system interception by the trees and crops was over 40 % greater than that for the sole trees and double that for the sole crop (Figs. 6.4 and 6.7). There have been several reports of increases in the dry matter:radiation use coefficient (e) in intercrops relative to sole crops, such as the groundnut/pearl millet intercrop studied by Marshall and Willey (1983) who found a 46 % increase in the e value for the shaded intercrop groundnut relative to the sole crop; this situation is likely to occur when shading of the understorey C3 crop limits the frequency of light saturation of photosynthesis which occurs at higher irradiances.

8.4 IMPLICATIONS FOR AGROFORESTRY SYSTEMS

Tree selection for agroforestry

Two main factors must be considered when selecting trees for agroforestry; firstly, what does the farmer want and need, and, secondly, what are the biological attributes of the species that will best meet these requirements within an agroforestry environment. As previously mentioned, in a survey of farmers in the Embu and Meru districts of Kenya, Spiers and Stewart (1992) found that the principal reasons cited for planting grevillea were the production of timber, fuel, poles, windbreaks, fodder and erosion control, in descending order of priority.

Previous selection programmes for grevillea have concentrated on supposedly desirable attributes such as height and growth rate (Kallinganire and Hall, 1993). The baseline selection procedure for grevillea parent stock in western Kenya adopted in ICRAF's multi-purpose tree improvement work has included criteria describing stem height,

diameter, bole form and straightness, crown diameter and wood density (Esegu and Odoul, 1992). However, characteristics which increase complementarity constitute more appropriate selection criteria for trees to be used in agroforestry systems. Harwood and Owino (1992) suggested that a sparse, narrow crown and deep-rooting habit would contribute to the ideal grevillea phenotype for agroforestry, and it is possible that the complementarity of grevillea might be further improved by breeding or selection for these traits.

When upperstorey trees are to be combined with crops, criteria for factors which enhance the likelihood of temporal or spatial complementarity should be included in any selection procedure, in addition to the more conventional growth and height criteria. Thus, to allow more effective combinations with C4 crops, trees such as *Faidherbia albida* might be selected, not primarily for their growth rates or annual height increments, but for phenological characteristics which minimise the shading of understorey crops during the rainy season. For combinations with both C3 and C4 crops, a deep-rooting habit, with limited shallow roots would be an obvious selection criterion for agroforestry tree species in order to maximise below-ground complementarity. Flanagan *et al.* (1992) used the isotopic discrimination method for plant stem water described by Dawson and Ehleringer (1991) to distinguish between the use of summer precipitation and groundwater in trees and shrubs, and found that some trees used significant quantities of summer precipitation, whereas one species (*Chrysothamnus nauseosus*) appeared to depend exclusively on groundwater. This approach could be used to assess the likely competitiveness of multipurpose tree species; for example, any increase in the proportion of dry season precipitation used by trees is likely to reflect greater root activity in the surface horizons and hence an increased likelihood of below-ground competition, rather than complementarity. Alternatively, a combination of root excavations with sap flux measurements (cf. Sections 4.8 and 7.3) could be used to assess the extent of potential below-ground complementarity of tree species; this method could be employed for both on farm and on-station sites, and has the advantage of providing meaningful results within a restricted time period.

The reductions in crop yield resulting from interception losses of precipitation in CIRUS

indicate the importance of canopy size and structure in determining the success of tree/crop combinations. Interception is dependent on rainfall distribution, local climatic factors and the properties of the canopy involved. Calder (1992) compared reported interception losses for a several species and found that these ranged from 11-34 %. George (1978) reported interception losses of 12 and 27 % for a *Eucalyptus* hybrid and *Pinus roxburghii* in India (average rainfall, 1670 mm), while Monteith *et al.* (1991) reported a value of 40 % for a leucaena-based system. Canopy storage is the term given to the quantity of water that can be held by a canopy after saturation (pending evaporation), and has been reported to be as large as 8.3 mm for some tropical rainforest trees (Herwitz, 1985). Crown storage (storage by individual trees rather than the entire canopy) is likely to be relatively consistent for trees of a specific variety, and age, when grown under similar management and climatic conditions; storage is a key factor in determining the extent of interception losses and might form a useful criterion for screening. The method adopted by Teklehaimanot and Jarvis (1991) to establish crown storage capacity by suspending excised trees from a load cell before spraying the canopy with water (cf. Section 1.5) could be used as a basis for screening, and might be applied on a small scale using severed branches rather than whole trees, although variation in branch orientation and architecture would necessitate repeated measurements. Given the wide range of interception losses reported by Calder (1992) and George (1978), this is an area worthy of further research.

Crop selection for agroforestry

The substantial crop diversity that existed in East Africa prior to colonisation has been replaced by a far narrower range of species (Gelfan, 1971). In Kenya, the current preference for maize has led to its planting in inappropriately arid areas such as Marsabit, which is prone to multi-year droughts with annual rainfall in 1992 of 80 mm (World Concern, pers. comm.). To an even larger extent than trees, crop selection must meet local preferences first and environmental constraints second if it is to be locally acceptable.

The minimum vegetative mass (W_v) that a plant must acquire before dry matter can be allocated to its reproductive or economically useful parts varies dramatically, from

around 1 g plant^{-1} for some varieties of rice to 80 kg plant^{-1} in oil palm (Squire, 1993). Given the hypothetical situation where water is the limiting resource and seasonal rainfall is barely sufficient to allow the sole crop to exceed W_v, then any reduction in water availability to crops grown with trees resulting from competition with the trees is likely to prevent the crop from reaching its critical W_v; this may even occur in agroforestry systems which exhibit substantial complementarity and little competition between trees and crops. Harvest index in the ABG maize decreased dramatically from 0.50 to 0.12 when total dry matter fell from c. 68 to 35 g plant^{-1}(equivalent to 300 - 160 g m^{-2}; cf. Fig. 3.4). Although the harvest index of cowpea also decreased as dry matter declined (Fig. 5.14), its HI values remained between 0.33 - 0.40 when dry matter fell below 50 g m^{-2}, equivalent to <3g plant^{-1}. The greater plasticity of cowpea in terms of maintenance of some yield under extreme conditions is a useful attribute for agroforestry in semi-arid areas with high interseasonal variability in rainfall. In some instances, intercropping has been shown to increase HI, such as when sorghum is intercropped with groundnut (Azam-Ali *et al.*, 1991).

Other desirable attributes for understorey agroforestry crops are generally similar to those for sole crops, and include resistance to pests and diseases, high harvest indices and stable yields (Loomis and Connor, 1992). As previously mentioned, shade tolerance constitutes an obvious additional attribute for any understorey crop grown in an agroforestry system involving upperstorey trees.

Hedgerows and runoff

Measured runoff in CIRUS accounted for 4 % of rainfall during the 1993/4 short rains (Table 7.7). At an adjacent site in Machakos, Kiepe (1995) measured runoff over six rainy seasons and found that the average for sole maize plots was equivalent to 3 % of the annual rainfall and that, although the presence of *Cassia siamea* contour hedgerows (4 m spacing) reduced runoff by over 75 %, this amounted to little more than a 2 % reduction in water losses when expressed in terms of seasonal rainfall. The presence of leucaena hedgerows in the rainfed ABG trail resulted in an 18 % reduction in maize yield relative to the sole maize, clearly demonstrating the potential competitive effects of a hedgerow system with an effective row spacing of 15 m; at a hedgerow spacing of 4 m,

a decrease in yield of maize well over 50 % (68 % if maize yield is linearly related to leucaena hedgerow density) might be expected. There is clearly a need to achieve a suitable balance between minimising competition and reducing runoff, and hedgerow systems are particularly suited to achieving the latter objective in high rainfall areas with moderate to steep slopes. In some cases runoff has been reported to account for as much as 25 % of the annual rainfall on gentle slopes of <3 % due to poor infiltration and/or high intensity rainfall (Hoogmoed and Stroosnijder, 1984); hedgerow systems may also be applicable in such situations. Kiepe (1995) suggested that an appropriate balance between limiting competition and reducing runoff may be achieved, at least to some extent, by combining a greater inter-row spacing of the hedgerows with a higher tree density within the hedgerow to reduce the area of the crop/hedgerow interface while still maintaining an effective physical barrier to runoff.

Windbreaks and shelterbelts

The use of shelterbelts and windbreaks to protect crops from mechanical damage and increase the dry matter:water use ratio is well documented (e.g. Stigter and Baldy, 1995). In a study of the effects of *Eucalyptus camaldulensis* shelterbelts on the growth and yield of millet, Onyewotu *et al.* (1994) demonstrated that reductions in millet yield occurred at distances from the tree row equivalent to 1.5 times the height of the trees (12 m), with trees roots being present in the surface soil horizons up to that distance from the trunk. The reductions in cowpea yields in the CTa treatment of CIRUS would have extended up to an estimated distance of 5 m from the tree row (greater than the mean tree height), probably due principally to interception losses of rainfall (cf. Section 7.7). These examples indicate the potential problems that may be experienced with shelterbelts, below-ground competition for water and/or interception losses may play a significant role in reducing water availability to the shelter crop.

In a study of windbreak interactions with a double row of neem trees (*Azadirachta indica* A. Juss.) and a millet crop in the Sahel, Brenner *et al.* (1995a, b), suggested that shelter may increase the dry matter:water use ratio in well-watered crops where shelter increases humidity more than temperature, but not in drying crops in which air temperature may increase disproportionately. Thus shelter belts may provide benefits under irrigation or

in areas where adequate rainfall is received, but may be counter-productive under water-limited rainfed semi-arid or arid conditions. As shelterbelts are typically planted at 100-300 m intervals, the area of the tree/crop interface is considerably smaller than in many agroforestry systems. However, since below-ground competition extended up to 18 m from the *E. camaldulensis* shelterbelt mentioned previously, direct tree/crop interactions may be expected to have occurred over 30 % of the cropping zone since the shelterbelts were 114 m apart (Onyewotu *et al.*, 1994); deep-rooting trees, with few shallow roots, such as grevillea, would be an obvious choice for such systems, although the extent and importance of interception losses would have to be determined. Slow growing trees, with low rates of resource use and limited competition may also be suitable as shelterbelt species, but the increased time required to establish such shelterbelts would pose an obvious drawback.

Experimental design

The ABG trial demonstrated that the effects of below-ground competition extended over distances of up to 6 m from hedgerow leucaena and to over 7.5 m from upperstorey leucaena into the associated maize crop (Fig. 3.2). This has obvious repercussions for experimental design, with large plot sizes and appropriate management being necessary to prevent the lateral growth of tree roots compromising adjacent plots in different treatments. Ong *et al.* (1996) stated that tree roots may extend laterally by up to 2 m per year and suggested that interference between plots may be a major problem. They also suggested that the spread of lateral roots outside the plot boundaries may lead to overestimation of within-plot resource capture by the trees. The 0.5 m deep root barriers used in the ABG trial proved insufficient to prevent below-ground competition between trees and crops. In Heineman's (1995) alley cropping trial involving mixtures of maize and *Leucaena leucocephala*, *L. coliinsi* and *Gliricidia sepium*, the plots extended for only 1.5 m either side of the tree rows, with no space between plots; thus the rows of the different tree species were only 3 m apart and the integrity of the plots was compromised by the inevitability of tree roots extending into adjacent plots. Whilst trenching or root-barriers may be employed to control root spread and interference, the prevention of interference between plots resulting from rainfall interception and shading can only be accomplished with careful experimental design and adequate plot sizes. The sole crop

yield is the usual baseline for comparison and it is of particular importance that its yield is not suppressed by competition from trees in neighbouring plots since depression of the control crop yield would lead to incorrect assumptions about the viability of the agroforestry systems with which it is being compared. Therefore sole crops in particular should not be surrounded by treatments containing trees, and plot sizes and inter-plot areas or guard rows should be of sufficient size to allow sections of each plot to be harvested without interference from neighbouring treatments.

Whereas poor experimental design may lead to interference between plots, sub-optimal sole crop or sole tree management may result in false assumptions concerning overyielding by tree/crop mixtures. Thus Corlett (1989) recorded LER values >1 for a leucaena/millet alley crop in semi-arid India, but concluded that the values obtained may have been artificially high due to the sub-optimal density of the sole tree plots; sound agronomy is therefore essential for the sole crop and correspondingly sound silviculture is required for the sole trees if optimal yields are to be achieved which will permit valid comparisons with the agroforestry systems being examined.

In CIRUS, plot soil depth was found to affect crop yield significantly in all seasons except the abnormally wet 1992/3 short rains. The extent of the variation in soil depth did not become apparent until after the trial had been established and the neutron probe access tubes were about to be installed. When the variation in soil depth was surveyed and incorporated into the analysis this allowed the extent of tree/interactions to be revealed (e.g. Table 5.12 and 5.13). If soil depth, particularly shallow areas which might limit the depth of tree or crop rooting, is not incorporated into the design and analysis of agroforestry experiments, the results may well be compromised; increased variability may mask treatment effects or, if the soil depth varies systematically within the experiment, treatment effects may be assumed when they are purely a manifestation of soil depth.

One of the problems inherent in research in areas with high inter-seasonal variability in rainfall is the difficulty of extrapolating results to other sites or future seasons; there is rarely a typical season and events occurring during one season may influence tree or crop

performance during the following season. For instance, if the short rains of 1992/3 had been near average in terms of rainfall, instead of more than double the seasonal average, the grevillea might have shed its leaves during the following dry season since Harwood (1992) suggested that complete leaf fall may occur in grevillea during drought. The leaf area of the trees would therefore have been smaller during the ensuing short rains, resulting in reduced interception losses and transpiration by the trees and increased yields from the intercropped cowpea. Thus, extrapolation of results from a single site and limited number of seasons must be based on a detailed understanding of the processes involved in determining tree and crop yields; certainty can only come from the integration of results from multi-site, multi-season trials.

Conclusions

Tree species such as grevillea offer cause for optimism, due to their deep rooting habit and correspondingly substantial below-ground complementarity. However, the study of complementarity in the use of below-ground resources by trees and crops needs to be greatly expanded if agroforestry is to achieve its much vaunted potential. For example, site-specific factors which modify root distribution and function need to be distinguished from genetically determined traits in order to identify complementary tree/crop combinations. The emphasis in previous selection and breeding programmes for multi-purpose trees has usually been directed towards above-ground characteristics, but it is clearly essential to include complementarity of root behaviour within the selection criteria. Given the large variation in reported interception losses (11-40 %; Monteith *et al.*, 1991; Calder, 1992), field trials involving the more popular multi-purpose trees to establish the relative importance of crown storage and interception losses must have a high priority. Possession of a shallow rooting habit may lead to increased resource capture by the trees within the surface soil horizons and substantial reductions in resource capture by associated crops in the absence of any net loss of resources to the system; in contrast, large interception losses may lead to a reduction in water availability to the crop in the absence of any significant increase in resource capture by the tree component, resulting in a net loss of resources to the system.

The radiation and water use efficiencies of C4 plants grown under near-optimal

conditions of water status, radiation, temperature and nutrients are generally substantially greater than in C3 species (Squire, 1990; Jones, 1992). The search for effective agroforestry systems containing C4 crops should therefore focus on trees that cast minimal shade during the cropping season such as *Faidherbia albida* (e.g. Monteith *et al.*, 1991; ICRAF, 1992). Leucaena has proved to be highly competitive and unsuitable for agroforestry in water-limited environments, whereas grevillea has shown the potential for successful combination with shade tolerant understorey crops. Leucaena exhibits characteristics typical of a "boom or bust" invasive, with shallow roots and limited stomatal control of water use, while grevillea appears to be more conservative, with deep roots, a persistent canopy and effective stomatal control. However, the existence of approximately 50,000 species of tree suggests that selection should perhaps be the principal focus in future, rather than the adoption of intensive improvement and breeding programmes.

Soil evaporation constituted the largest loss of water from CIRUS (Fig. 7.27) and probably also from the ABG trial; apparent reductions in soil evaporation in the CTd and Td treatments due to shade were more than offset by rainfall interception losses from the tree canopy. The addition of mulch did not reduce soil evaporation and there are no easy options for controlling this, the largest loss of the most limiting resource. The roles of shade, mulch and vegetation canopies in moderating soil evaporation are worthy of further research.

Ong (1995) emphasised the need to avoid over-complicating agroforestry research with an excessive number of secondary and tertiary order interactions. While a holistic understanding is desirable, we are still at the stage of determining the first order interactions that decree the success or failure of agroforestry systems.

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